22 What Are Shock Waves?

Achim M. Loske

Abstract Extracorporeal shock wave lithotripsy (SWL) has become the primary, noninvasive treatment modality for patients with stones in the kidney or ureter. Given this, it is essentially mandatory for all urologists to have basic knowledge of shock waves so that they may perform safer and more efficient SWL treatments. Unfortunately, most of the literature on shock wave physics is highly specialized. With this in mind, the aim of this chapter is to provide an easy to follow description of what lithotripter shock waves are. This chapter may also serve as a guide for physicians working on non-urological shock wave lithotripsy or other clinical and experimental applications of shock waves to medicine. The physics behind shock wave lithotripsy is quite a large subject, so a special effort has been made here to focus the discussion on an understanding of what shock waves are.

22.1 Introduction

Motivated by the success of extracorporeal shock wave lithotripsy (SWL), underwater shock waves have been the subject of considerable research in the last 25 years. The study of shock waves belongs to the field of acoustics, which is an interesting and broad field having applications in physics, engineering, biology, medicine, architecture, aeronautics, music, noise control, and many other topics. In general, the literature describing the physics of shock waves is highly specialized and difficult to follow by readers without a solid background in physics.[1] The objective of this chapter is to provide a useful and easy to understand description of shock waves and their applications in medical fields.

This chapter may also be useful to physicians working on other clinical and experimental applications of shock waves to medicine, like non-urological SWL,[2–4] orthopedic application of shock waves,[5,6] treatment of refractory angina pectoris, the possible treatment of Peyronie's disease,[7,8] cell transfection, tumor therapy,[9–12] thrombus ablation,[13] and inactivation of bacteria with shock waves.[14–16]

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22.2 Waves

It is important to distinguish between two main types of waves: *mechanical* waves and *electromagnetic* waves. Electromagnetic waves – such as light, laser waves, radio and television signals, microwaves, and X-rays – do not require a medium to propagate. In this case, so-called "electric fields" and "magnetic fields" oscillate in a plane perpendicular to the direction of wave propagation. Since shock waves do not belong in this category no more information on electromagnetic waves will be given in this chapter.

22.2.1 Mechanical Waves

All mechanical waves are generated by a source, which causes a disturbance in the medium. It is this disturbance traveling through a medium that is called a "wave" (Fig. 22.1). Unlike electromagnetic waves, mechanical waves require a medium for propagation and cannot travel through a vacuum. This is essentially because mechanical waves are made up of vibrations of the molecules that make up the medium. These vibrations spread throughout the medium and energy is transferred from one molecule to the next. It is important to note that waves carry energy – not matter – over large distances. Individual particles (molecules) oscillate a small

P.N. Rao et al. (eds.), *Urinary Tract Stone Disease*,
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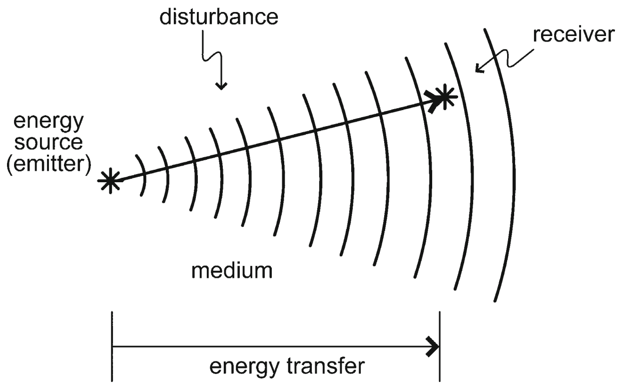

Fig. 22.1 Schematic of a mechanical disturbance traveling through a medium. The wave transports energy from the source to the receiver

distance, but do not travel along with the wave. In addition, as the wave moves through the medium, there is a loss of energy due to friction. In general, the pressure "amplitude" of the wave decreases as the distance traveled increases.

Examples of mechanical waves are shock waves, sound, vibration, seismic waves, water waves, and ultrasound. Mechanical waves can be regarded as useful or useless. Very useful mechanical waves are speech and music, while generally useless sound waves in air are called "noise." Many vibrations are also considered useless or even dangerous. In most situations, both useful and useless waves will be present.

22.2.2 Transverse Waves

Mechanical waves are further divided into two groups by the type of motion that the molecules execute: *transverse waves* and *longitudinal waves*. In transverse waves, the motion of the particles is perpendicular to the propagation of the wave. This is easily visualized, by imagining a floating object, while a so-called "surface" wave passes by (Fig. 22.2). Another example is the case of waves that propagate on a string. Transverse waves are sometimes referred to as *shear* waves.

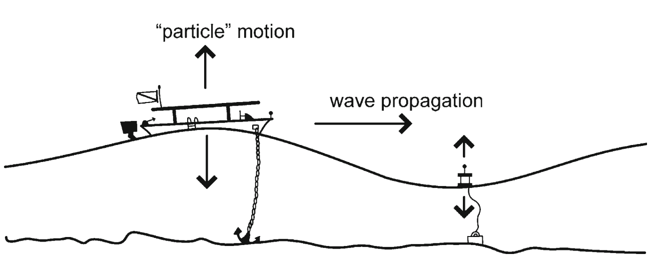

Fig. 22.2 A boat floating on the ocean with the engine turned off moves perpendicular to a passing wave. Particles always move perpendicular to the propagation of transversal waves

22.2.3 Longitudinal Waves

In a longitudinal wave, all particles oscillate parallel to the direction of propagation. They are also called *compressional* waves. A well-known example is the compression (and *rarefaction*) of the segments of a spring as a wave travels along its length. Sound, which is produced by variations in the density of air, is also a longitudinal wave (Fig. 22.3). At a particular point in space, "sound" is a rapid variation in the pressure of a medium around a steady-state value. This steady-state pressure can be, for example, the atmospheric pressure or a hydrostatic pressure (the pressure caused by the height of a liquid above a certain point of reference). Since all states of matter can be compressed, longitudinal waves propagate through solids, liquids, and gases. It is important to remember that the individual particles of the medium are only displaced locally; the only thing that travels all the way from the source to the receiver is the wave itself. The wave's speed, referred to as the *speed of sound* or *speed of wave propagation,* depends on the density, the elasticity, and the temperature of the medium. The speed of propagation is much higher in a solid medium than in a liquid medium as the restoring force between individual molecules is much higher in a solid. Furthermore, at higher temperatures, molecules move faster and collide with each other more often. One therefore finds that mechanical waves propagate faster as the temperature of the medium is increased. For instance, the speed of sound in pure water at 0°C is approximately 1,400 m/s while its speed at 30°C is about 1,510 m/s.

22.2.4 A Few Definitions

There are several definitions used in physics to describe the properties of a wave. It is important for any physician to distinguish clearly between these definitions as they may frequently appear in treatment protocols, equipment specifications, and scientific articles.

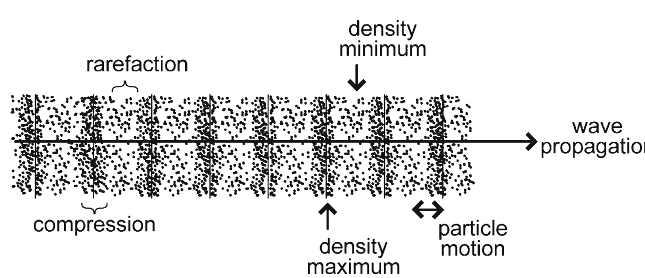

Fig. 22.3 A longitudinal wave is characterized by the propagation of rarefactions and compressions of the medium. Particles oscillate parallel to the direction of the wave propagation and are not transported from the emitter to the receiver

If a small spherical object is dropped into a pool, circular ripples travel outward from the spot where the object hit the water. All points on a specific ripple that are in the same state of motion are on a surface called a *wavefront*. One may imagine lines drawn perpendicularly to the wavefronts; these are called *rays* and are often used to show the path of a wave as it propagates (Fig. 22.4). Waves can spread in one, two, and three dimensions. For medical applications, the study of three-dimensional wave propagation is the most important. In three dimensions, one may imagine wavefronts with a spherical shape, with associated rays being radial lines.

The *wavelength* is defined as the distance between two successive peaks or two successive troughs (Fig. 22.4). The time interval between the passage of two successive peaks or troughs is called the *period*. Some textbooks also define the period as the time it takes a wave to complete a *cycle* (Fig. 22.5). The *amplitude* is defined as the *height* of the wave, generally measured from the baseline to the highest (or lowest) value. The amplitude may refer to the actual height of a water wave above the water's still height or to the *pressure amplitude* (that is, the difference between the pressure in highly compressed regions and some specified baseline pressure).

A well-known parameter used to describe a wave is its *frequency* – this is the number of cycles that pass by a certain position in 1 s – which is measured in hertz (Hz). In other words, the frequency gives information on how many wavelengths happen in 1 s. A concept that may be somewhat more difficult to imagine is that of a *frequency spectrum.* The fact is that all waves, even non-periodic waves, can be built up by the superposition of a series of *harmonic* waves of different frequencies and amplitudes (Fig. 22.6). A mathematical technique, called *Fourier analysis,* is used to calculate the

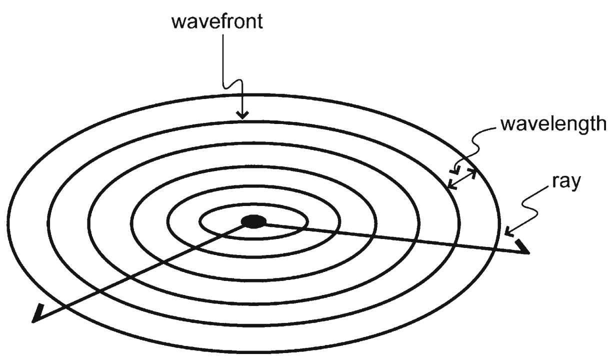

Fig. 22.4 Schematic of a circumferential surface-wave propagating through a liquid. Each circle corresponds to a crest. The wavelength can be determined by measuring the distance between two consecutive crests. Rays are imaginary lines that indicate the direction of propagation. They are drawn perpendicular to the wavefronts. In this figure, rays are directed radially, away from the source

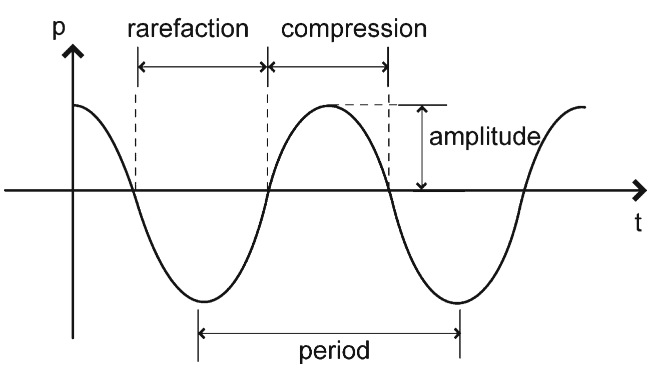

Fig. 22.5 Graph of pressure as a function of time, showing how the pressure changes as a longitudinal wave passes a certain point in space. The sinusoidal shape of this pressure variation should not be confused with a transversal wave moving through space. This plot gives information on how the pressure varies *in time*

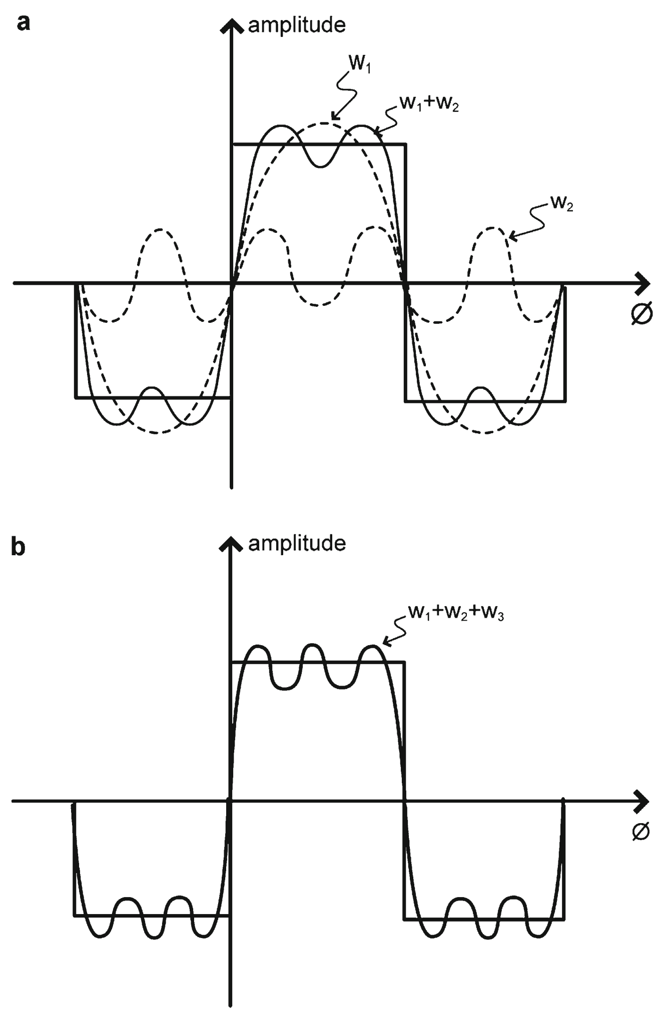

Fig. 22.6 Any wave can be imagined as the superposition of a certain number of harmonic waves (w_1, w_2, w_3…) with specific frequencies and amplitudes. The sum of only two harmonic waves ($w_1 + w_2$) is a bad representation of the square wave shown in (**a**). Adding one more harmonic wave ($w_1 + w_2 + w_3$) improves the result (**b**). The similarity between the original profile and the sum of harmonic waves increases as the number of harmonic waves increases. It would be necessary to draw the sum of a large number of harmonic waves with the adequate amplitude and wavelength to represent the square wave adequately

frequencies, amplitudes, and phases of the harmonic waves (w_1, w_2, w_3…) that have to be added to synthesize the desired waveform. The number of harmonic waves needed to describe a non-periodic wave depends on the profile of the wave. A sinusoidal wave is periodic (and harmonic) and has only one fundamental frequency associated to it. A lithotripter shock wave, which is a single high-pressure peak with a steep onset and a gradual decline into a pressure trough, is non-periodic and can be imagined as consisting of a large number of waves of different frequencies.

The *power* of a wave, measured in watts (W), is defined as the energy transported by the wave during a certain time interval. Furthermore, the power delivered by a wave per unit area (i.e., per square meter) is called the *intensity*. The standard units of intensity are watts per square meter (W/m^2). Since the energy emitted from a point source spreads out in all directions, its intensity will decrease with radial distance from the source. The intensity of a wave is proportional to the square of its amplitude. As the measured values of sound intensity have an expansive range, a logarithmic scale is typically used. Sound intensities are normally given with respect to a reference, the threshold of hearing: $I_o = 10^{-12}$ W/m^2. The *sound level* is defined as 10 log (I/I_0), where I is the intensity in W/m^2 to which the sound level corresponds. Sound levels are expressed in *decibels* (dB).

Shock waves undergo *refraction* and *reflection* when passing from one medium to another. Refraction occurs as shock waves enter the patient's body. An important definition related to the reflection of acoustic waves is the *specific acoustic impedance*, or simply the *acoustic impedance,* of a medium. The acoustic impedance measures the ease with which the wave propagates through a certain material. For a *plane wave*, the impedance is just the product of the density of the medium and the wave speed.

22.3 Shock Waves

In general, the word *sound* is used to describe waves in the frequency and intensity range that our auditory system is capable to detect (about 20 Hz–20 kHz). The science of acoustics, however, also includes the study of waves that we cannot hear (Fig. 22.7). Acoustic waves having a frequency below the frequency limit of our ears are called *infrasound*. *Ultrasound* refers to waves with frequencies above our range of hearing. Shock waves are sometimes referred to as ultrasound or *explosive ultrasound* waves because they share some properties with ultrasound. Though similarities exist, one should not confuse shock waves with the type of ultrasound used in diagnostic imaging systems or therapeutic applications (such as high intensity focused ultrasound and focused ultrasound surgery). For instance, the pressure amplitude generated by a lithotripter shock wave can have up to 75 times the pressure amplitude of the waves used in diagnostic ultrasound.

Shock waves are transient pressure changes that propagate

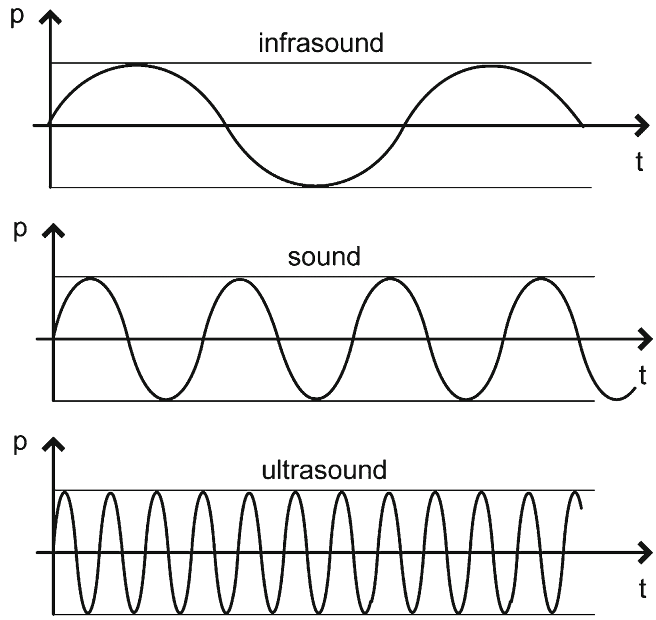

Fig. 22.7 Graphs of pressure as a function of time for harmonic waves. According to their frequency, acoustic waves are classified as infrasound, sound, or ultrasound

through three-dimensional space. They result from a very fast release of a large amount of energy in a relatively small space. Shock or *blast waves* differ from acoustic waves (which consist exclusively of small pressure changes) in that they may propagate in a manner entirely different from that of ordinary acoustic waves. An example is the acoustic boom following a lightning bolt during a thunderstorm. The initial shock wave pressure decays as the wave expands until it degenerates into a sound wave. This is inevitable as a fixed amount of energy has to be spread out over an ever-increasing volume. The detonation of an explosive and the passage of supersonic aircraft are also well-known examples of shock wave generation (Fig. 22.8). Shock waves can be produced in all states of matter. It is not usually possible to see a shock wave; however, shock waves can be made visible with suitable optical instrumentation.

22.3.1 Lithotripter Shock Waves

22.3.1.1 Shock Wave Generators

Extracorporeal shock wave lithotripters consist of a shock wave head (shock wave source), a treatment table, and a localization system (a coaxial or lateral ultrasound imaging

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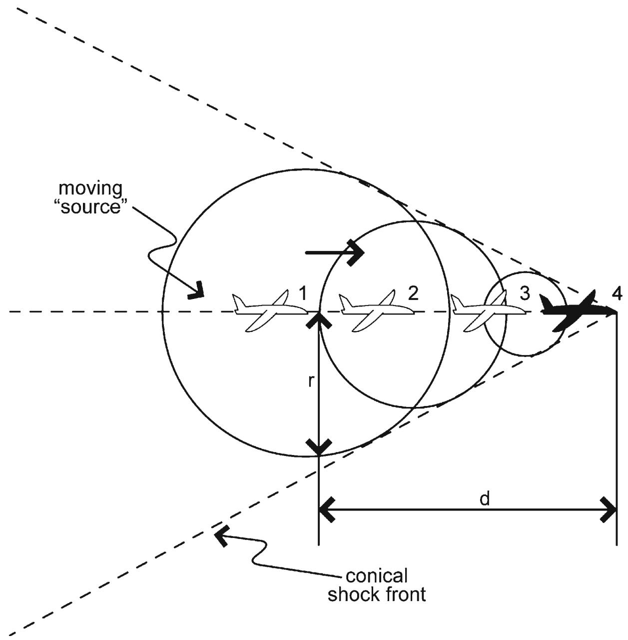

Fig. 22.8 Schematic of the shock front produced by a supersonic aircraft moving at a speed greater than the speed of sound. The aircraft traveled a distance *d* (from point 1 to point 4) in the same time needed for the wave, generated at point 1, to travel the distance *r*. The envelope of the three-dimensional pressure waves produced is a three-dimensional cone. Its angle depends on the speed of the aircraft

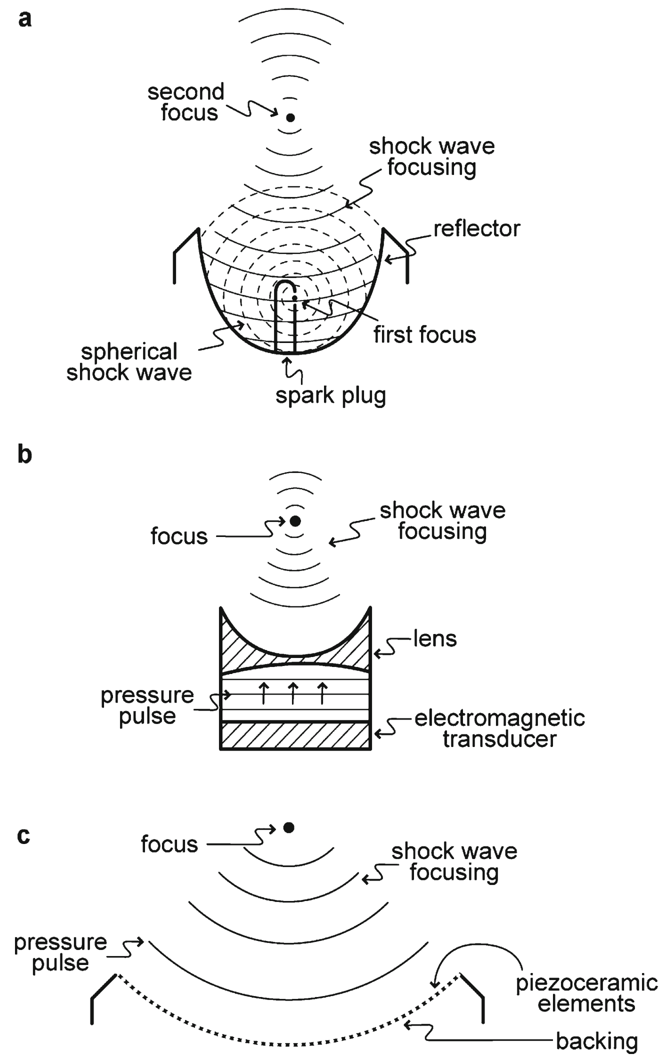

Fig. 22.9 Schematic of three different shock wave generation principles. (**a**) Electrohydraulic lithotripters produce shock waves by electrical breakdown of water at the first focus of a metallic ellipsoidal reflector. Part of the spherical shock front is reflected off of the reflector and focused at the second focus. (**b**) Electromagnetic lithotripters generate pressure pulses by moving a metal diaphragm, located at the base of a water-filled shock tube. Magnetic forces cause the membrane to be repelled, transmitting mechanical energy to the water. The flat pressure wave induced by the sudden movement of the membrane is focused by an acoustical lens. Shock waves are formed only *after* passage through the lens. (**c**) Piezoelectric lithotripters consist of a set of piezoelectric crystals mounted on a hemispherical bowl-shaped aluminum backing. A high-voltage pulse applied to all crystals at the same time causes their rapid expansion, producing a pressure wave in the water. A shock wave arrives at the focus after superposition of the pressure wave formed by each crystal

system and/or an isocentric C-arm fluoroscope). It is not the purpose of this chapter to describe the details of shock wave generators; however, having some information on their working principles is useful to better understand what lithotripter shock waves are. More information on extracorporeal lithotripters can be found in the literature.[17–19]

Nowadays, there are three main shock wave generation techniques on the market: electrohydraulic, piezoelectric, and electromagnetic (Fig. 22.9). All release large amounts of energy inside a transducer and generate shock waves outside the patient's body. To prevent shock waves from losing energy, focusing devices like lenses or reflectors are needed. In electrohydraulic lithotripters, shock waves are generated by an underwater high-voltage spark that is discharged between two electrodes (the arc is localized in the first focus of an ellipsoidal reflector, see Fig. 22.9a). The fast expansion of the *plasma* bubble at the first focus generates a shock wave, which propagates spherically outward and reflects off of the metallic reflector. The shock front gets focused toward the second focal point. Shock waves reflect off of the reflector of an electrohydraulic lithotripter in a manner similar to that found in optical waves. This is because under certain circumstances the same law of reflection is followed by both sound and light. The low-energy unfocused part of the primary spherical shock wave will always propagate through the patient. The first spark-gap lithotripters were manufactured by Dornier Medizintechnik GmbH in Germering, Germany.

Three different electromagnetic systems are in use. The classical shock wave head, designed by Siemens GmbH in Erlangen, Germany, generates pressure pulses by moving a circular metal diaphragm that is placed in a water-filled shock tube (Fig. 22.9b). A high voltage pulse is sent through a coil, placed behind the diaphragm, so that it is repelled. A lens focuses the pulse, forcing its pressure profile to steepen, quickly transforming the pulse into a shock wave. Coupling of the shock wave to the patient is done using a water-filled cushion. The second type of electromagnetic shock wave generator (not shown in Fig. 22.9), uses a cylindrical coil to produce a cylindrical wave that is reflected by a parabolic reflector and transformed into a spherically focused shock wave. This shock wave generator, manufactured by Storz Medical AG in Kreuzlingen, Switzerland, has also been very successful.[20,21] Using this shock wave generation principle, the manufacturer has also developed a shock wave head that allows the user to change the focal size, even during treatment. The third type of electromagnetic shock wave generator, manufactured by XiXin Medical Instruments Co. Ltd (not shown in Fig. 22.9), is a self-focusing design; it does not use a lens or a reflector to concentrate shock wave energy. Analogous to a piezoelectric lithotripter, this generator uses a spiral coil mounted on a spherical backing.[22]

Piezoelectric shock wave generators as manufactured by Richard Wolf GmbH are called self-focusing. These generators produce shock waves in water by exciting piezoceramic crystals. The crystals are arranged on the concave surface of a spherical metallic dish and expand suddenly when they are exposed to an electric discharge (Fig. 22.9c). The sudden displacement of the crystals produces a pressure wave with most of the energy focused toward the center of the generator. Relatively small piezoelectric shock wave heads, with two layers of piezoelectric elements, have become available.[19,23]

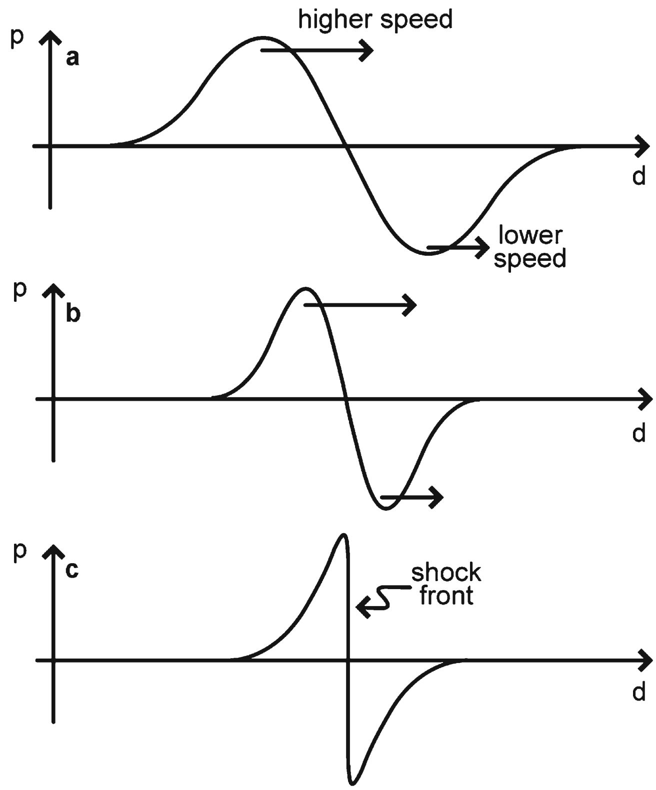

Fig. 22.10 Simplified graphs of pressure as a function of distance, explaining shock formation. If an acoustic wave, having high pressure propagates through a medium then the higher pressure parts travel faster than the lower pressure parts (**a**), distorting the shape of the wave (**b**). After traveling certain distance, a shock front is formed (**c**)

22.3.1.2 Shock Wave Formation

Spark gap generated shock waves are formed almost immediately after the electrical energy is released. In contrast, electromagnetic and piezoelectric lithotripters produce strong compressions that degenerate into a shock wave as they travel trough liquid. In piezoelectric lithotripters, the shock wave develops while the pressure pulse, generated by the piezoelectric transducer, travels toward the focus. In electromagnetic systems, the shock front develops after passing through the lens. At low-energy settings, some lithotripters do not produce shock waves at all (though any extracorporeal lithotripter pulses are typically called shock waves to denote the high amplitude of the pulse).

Recall that the speed of a mechanical wave increases as the density of the medium increases. As shock waves propagate, they transiently cause the medium to become denser. For small pressure amplitudes, each part of an acoustic wave travels at the same speed – the propagation speed; however, if the pressure differences are large, the sound speed is not the same for all points. In an extracorporeal lithotripter, a large positive pressure pulse is initially formed due to a sudden compression of the fluid contained inside the shock wave head. This compression pulse gets distorted as it travels through the medium. This is because high-pressure parts of the wave travel faster than the low-pressure parts. As the high-pressure parts travel faster, they increase the pressure at the wave front, pushing the wave profile forward. As this continues, a steep front, called a *shock front*, is formed. A compression pulse is fully transformed into a shock wave when the pressure profile ceases to pile up any further (Fig. 22.10). At this stage, the pressure and density along the shock front vary wildly in a very short region. The wavefront of a lithotripter shock front has a thickness less than 1 mm. Normally the entire pressure profile is called a shock wave; however, the word *shock* should only be used for the first fast pressure rise. Formally it is only the sharp positive pressure jump that is shocked. Shock fronts can have different amplitudes and widths. The steepness of the shock profile depends on the particular lithotripter.

22.3.1.3 Parameters Describing a Lithotripter Shock Wave

There is an international consensus that the most important parameters describing a shock wave for medical application are (Fig. 22.11): positive maximum pressure (p^+), negative

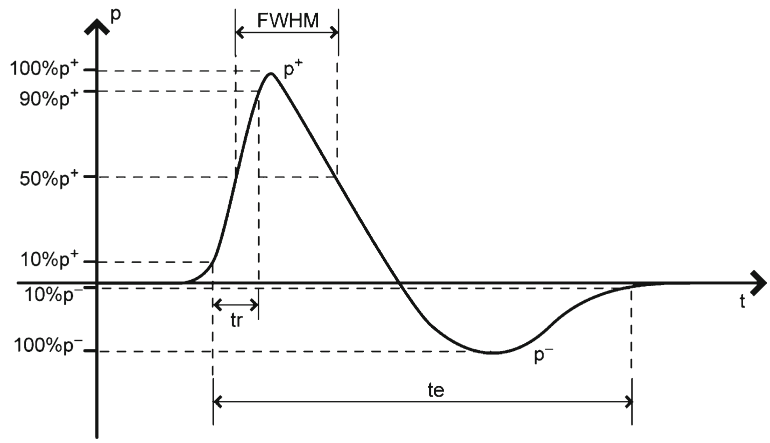

Fig. 22.11 Graph of pressure as a function of time, showing the most important parameters defining a lithotripter shock wave: *FWHM* full-width-half-maximum, t_r = rise time, t_e = time used to calculate the "total energy" of the shock wave, p^+ = positive maximum pressure, p^- = negative maximum pressure

maximum pressure (p^-), rise time (t_r), full-width-half-maximum (FWHM), energy flux density (EFD), and focal energy.[24]

The *positive maximum pressure* (p^+) is defined as the pressure difference between the maximum positive pressure of the shock wave and the ambient pressure. In an analogous manner, the *negative maximum pressure* (p^-) is the maximum negative pressure found in the tensile phase of the shock wave. The amplitude of p^- may be as much as 20% of p^+.

The time needed for the pressure to rise from 10% to 90% of p^+ is defined as the *rise time* (t_r). For lithotripter shock waves, t_r has the unbelievable value of less than 5 ns (five billionths of a second). The time interval between the instant when the pressure first reaches 50% of p^+, and the first time it falls under 50% (Fig. 22.11), is the so-called *full-width-half-maximum* (FWHM). This duration varies between about 0.2 and 0.5 µs.

The *dynamic focus*, *focal region*, or *−6 dB focal zone* of a lithotripter is defined as the volume in which, at any point, the positive pressure peak amplitude is equal to or higher than 50% of p^+. The size of this volume depends on the shock wave generation and focusing mechanism, as well as on the voltage setting. It is called the −6 dB focal zone, because −6 dB is equivalent to 50%. This definition is widely used among manufacturers; however, it typically does not give enough information for medical applications. One does not know enough about the energy contained in the focal volume and, as a consequence, one does not know enough about the stone disintegration efficiency of a lithotripter. Given this, a more convenient parameter to describe the performance of a shock wave generator has been defined: the *treatment zone* or the *5 MPa focus*. As shown in Fig. 22.12, the treatment zone is the volume inside which any point has a pressure equal to or larger than 5 MPa.[17] The 5 MPa figure is used as it has been identified (by the German Society of Shock Wave Lithotripsy) as the lowest pressure that is medically effective. Both of the focal volumes mentioned previously have the shape of an elliptical cigar. A noteworthy difference is that the −6 dB focal zone depends on relative pressure measurements, while calibrated (i.e., absolute) measurements must be used to set the limits of the 5 MPa focus.

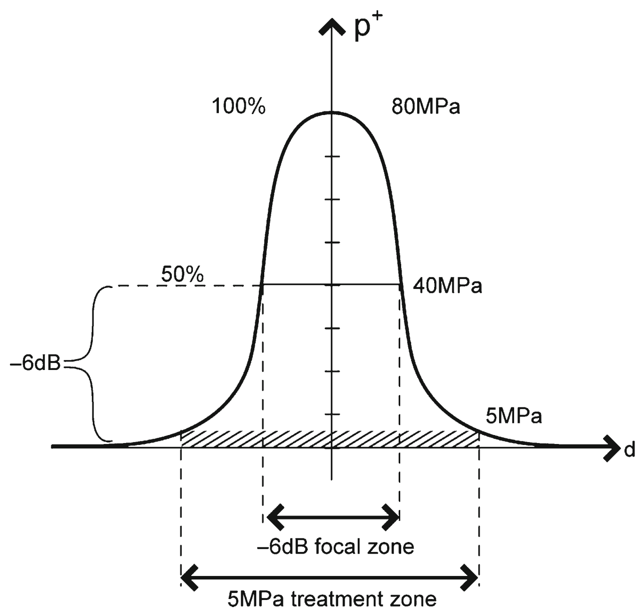

Fig. 22.12 Graph of pressure as a function of distance in the neighborhood of the focus of an extracorporeal lithotripter. The −6 dB focus and the 5 MPa treatment zone are compared

Another definition that will prove useful in SWL applications is the *energy density* or *energy flux density* (EFD). This is defined as the amount of energy transmitted through an area of 1 mm^2, per shock wave. It should not be confused with the *total acoustical energy* per released shock wave, which is the sum of all energy densities across the beam profile multiplied by the area of the beam profile. If only the positive phase of the shock wave is considered in calculating the energy density, the EFD is referred to as the *positive* EFD.

22.3.1.4 Shock Wave Pressure Profile

At the focal zone, extracorporeal lithotripters generate a strong acoustic field with extremely fast pressure variation. It is not easy to accurately record such a field (Fig. 22.13). Taking accurate pressure measurements of a shock wave that

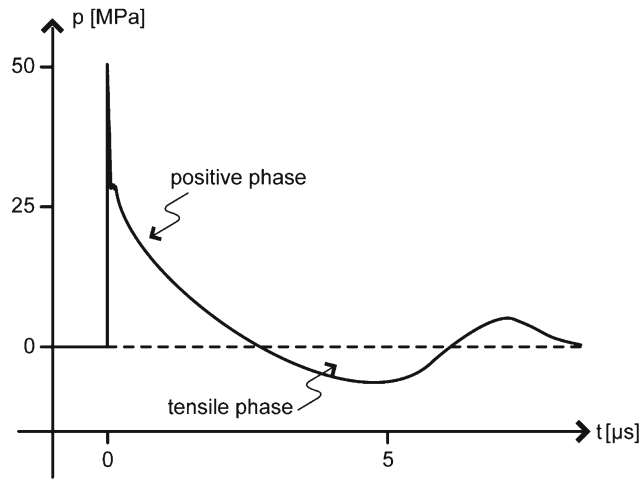

Fig. 22.13 Typical pressure profile recorded using a fiber-optic hydrophone (FOPH 2000, RP Acoustics) at the focus of an extracorporeal lithotripter. An extremely short positive pressure rise is followed by a fast pressure decrease and a pressure trough

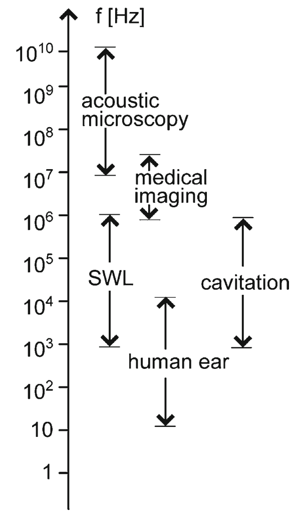

Fig. 22.14 Frequency spectrum showing the range of human hearing and extracorporeal shock wave lithotripsy (SWL) compared to other acoustical phenomena

lasts 1 μs or less and has a rise time of about 5 ns requires a pressure gauge with an extraordinarily fast response. Nowadays, the most convenient instruments to perform pressure measurements in SWL are the fiber-optic hydrophone,[25] and the light spot hydrophone.[26] Fiber-optic hydrophones were recommended as a measurement standard in 1998.

The pressure pulse in the focal region of a lithotripter consists of a short compression pulse with a peak pressure between 30 and 150 MPa, and a subsequent decompression pulse, sometimes referred to as the *negative* pressure peak or *tensile phase*. The tensile phase will typically have a tensile peak of up to −20 MPa and a phase duration of 2–20 μs. Lithotripter shock waves can be created over a broad range of frequencies, in about the 16 kHz range to about the 20 MHz range. The therapeutically effective components for SWL are above 200 kHz (Fig. 22.14). Most energy is between about 100 kHz and 1 MHz, with a peak at about 300 kHz. *Total pulse energies* are in the range of about 10–100 mJ[27] and *energy densities* are between about 0.2 and 2.0 mJ/mm^2. Time durations (i.e., the time between the positive peak and the negative peak) are similar in all lithotripters.

During SWL, stones fracture mainly due to spalling, cavitation, circumferential squeezing, superfocusing, and fatigue.[28,29] Most of these mechanisms act synergistically, rather than independently. For many years, other shock wave profiles have been proposed in order to improve calculi fragmentation with the least amount of tissue damage. The use of composite reflectors[30] or two confocal electrohydraulic lithotripters with a controlled delay between their pulses have been tested.[31] Results indicate that stone comminution can be enhanced, or tissue damage reduced, by controlling the delay between shock wave emissions. Another well-known example is that of tandem shock waves (Fig. 22.15). In order to understand the basics of this alternate pressure profile, it is

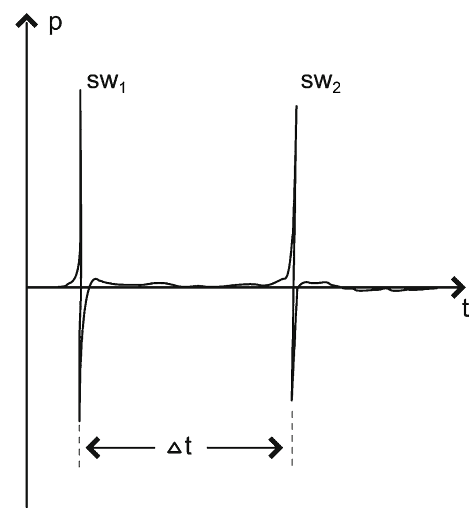

Fig. 22.15 Graph of pressure as a function of time at the focus of a piezoelectric tandem lithotripter, showing to similar shock waves (sw_1 and sw_2), arriving with a time delay Δ*t* (delta *t*)

helpful to recall the physics of acoustic cavitation.[32] During SWL, bubbles contained in the fluid near a calculus are compressed by the positive peak of each shock wave. As the tensile phase reaches these micro-bubbles, their volume increases significantly. After a few hundred microseconds, the bubbles collapse violently, generating secondary shock waves and high-speed microjets.[33,34] Comparison between the effects of cavitation induced by two different pressure–time shock waveform pulses was studied by Cathignol.[35]

Several authors showed that the energy of collapsing cavitation bubbles can be intensified if a second shock wave appears shortly after their stable phase.[36,37] The time delay between the first and second shock wave should correspond to the collapse time of the bubble cluster formed by the first shock wave. This type of lithotripsy, called tandem SWL, is still under research. No clinical results have been reported so far.

Tandem SWL should not be confused with *dual-head* SWL. Dual-head lithotripters, sometimes called dual-pulse lithotripters, have two separate shock wave generators. From the theoretical standpoint, dual-head lithotripters have interesting advantages but, nevertheless, they are not tandem lithotripters because they generate two pulses with a delay that is too long to enhance bubble collapse.

22.3.1.5 Shock Wave Attenuation

Experiments that attempt to use ultrasound for SWL have failed, as these waves are highly attenuated in tissue and pose some risk of thermal injury to the tissue.[38] Shock waves undergo less attenuation than ultrasound waves when propagating through tissue. This is because, in a biological medium, high frequency waves are absorbed more than low frequency waves. Since shock waves have lower frequencies than ultrasound waves, they have a higher penetration power.

Absorption in tissue is higher than in water. Since the shock front contains high frequencies, it is absorbed faster than other parts of the shock wave profile. After traveling a few centimeters through tissue, the amplitude of the shock wave reduces and its rise time increases. Despite this, the negative phase of the shock wave will remain almost unaltered.

Some studies have revealed that stone to skin distance may predict SWL outcome.[39] The amount of acoustic energy that is actually transformed into mechanical energy (energy that can be used to fracture a renal stone) depends on both the acoustic impedance of the media and on the angle of arrival of the shock wave. Peak-pressure attenuation of shock waves in water is about 10–20% for a distance of 100 mm while the energy attenuation due to passage of a shock wave through the membrane of a lithotripter water cushion is about 20%. Furthermore, poor coupling between patient skin and water cushion may increase shock wave attenuation up to 50% or more.

22.4 Conclusions

Intensive research has been carried out worldwide in order to find improvements in SWL technology that increase fragmentation efficiency while reducing renal damage. Stone location, composition, and the existence of a fluid-filled expansion chamber influence SWL outcome. Shock wave energy, the pressure profile, and the shape of the focal zone, as well as patient positioning and coupling are also crucial. As technology develops, it becomes more and more important for a physician to have basic knowledge in physics. Extensive training by certified technicians should be required in all lithotripsy centers to guarantee good results and to prevent overtreating.

What are shock waves? To imagine an event lasting a tenth of a second or even a hundredth of a second might be possible for most people. However, to visualize an event occurring in a millionth of a second is far beyond our capacity. As a lithotripter shock wave passes through water or tissue at a speed of more than 1,500 m/s, the pressure rises in one to five billionths of a second and returns to its original value in a few millionths of a second. In a time of five billionths of a second, the bullet of a firearm having a speed of 800 m/s only travels about four thousandths of a millimeter – a distance so small that a microscope is needed to see it! Shock waves are an incredible phenomenon, quite impossible to conceive with our senses.

Acknowledgments The author acknowledges Francisco Fernández, Ulises Mora, and Arturo Méndez for support. All figures were designed by Gabriela Trucco.

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