# Chapter 4
# Shock Focusing in Nature and Medicine

## 4.1 Introduction

Shock focusing in nature appears in different settings, from the deep ocean to outer space, but perhaps one of the most common occurrences is during the collapse of cavitation bubbles. Cavitation bubbles are generated in a wide range of different situations, for example, in trees and plants and by marine life with purposes of feeding, communication, and locomotion. In this chapter, we will discuss some of the occurrences of shock focusing in nature, without the influence of mankind. Much effort has been spent to further understand this phenomena, which often occurs at tremendously high speeds and at small scales as in a collapsing bubble or at very large scales as in a collapsing star.

Perhaps one of the most common occurrences of shock focusing in nature is in the ocean. It is well known that fast swimmers, like dolphins or tuna, can generate cavitation around the trailing edge of the rear fin. Dolphins are limited to swimming at speeds around 10–15 m/s because at higher speeds cavitation bubbles are formed, and once they collapse, the bubbles create jets that pit at the dolphin skin, a painful experience [20]. Tuna, on the other hand, do not have nerve endings at the bony tail fin, so they are not influenced by cavitation injury as dolphins are. However, the cavitation cloud forms around the tuna fin and effectively slows down the swimming speed.

Plants can also cause cavitation. The fern sporangium (which translated from Greek means spore vessel) is able to launch its spores at a tremendous speed of 10 m/s and an acceleration of $10^5$g. The launching mechanisms, which can be likened to a cleverly built catapult, are due to cavitation that occurs inside the cells of the annulus containing the spores [32]. As the cells of the annulus lose water due to evaporation, the vapor pressure becomes low enough to generate cavitation.

In vascular plants, xylem is one type of transport tissue, mainly with the purpose to transport water along with some soluble mineral nutrients from the root to the rest of the plant. To transport water from the soil to the top of the plant, a negative



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water pressure in the xylem is necessary. If at any point gas bubbles should occur in the xylem, cavitation can occur [49, 51]. This has negative effects for the plant as the xylem can be blocked and water transport is reduced.

## 4.2 The Fastest Gun in the Sea

If you were to guess what the loudest animal in the ocean is, you might not pick the Alpheidae (Decapoda, Caridea) shrimp, or more commonly referred to as a snapping shrimp, as your top guess. Surprisingly, the snapping shrimp generates enough noise to disturb high-frequency sonar systems, which are used by both humans and some marine animals for communication. Studies have shown that the noise generated by the snapping shrimp can be 40 dB higher than the ambient noise [22], and the noise from the shrimps have been likened to the sounds generated by popping popcorns [1] and by sizzling fat in frying pans [3].

The snapping shrimp is indeed a remarkable little animal. It prefers shallow waters, less than 60 m depth, and warm temperatures, higher than 11 °C [10]. The shrimp usually lives in burrows in coral reefs, in oyster reefs, or in submerged seagrass flats. Some species live in cohabitants with other marine critters, for example, with sea anemones [30], and other snapping shrimp live in large colonies, similar to bees and ants. In this case, the colony is ruled by a king and a queen, and they are the only ones that breed.

The shrimp is quite small and measures between 30 and 50 mm long. It has a strongly asymmetric look with one giant claw—which can be as large as half the shrimp—and one regular pincer claw, see Fig. 4.1. The oversized claw can be on either side of the body, and it is used as an "underwater pistol" to stun or kill prey, but it is also used for interspecies communication. The giant claw consists of an immobile part, called the propus, and a mobile part, called the dactyl. The dactyl has a plunger-like outgrowth that fits into a socket in the propus. To snap, the shrimp opens the dactyl to around a 100° angle using an opener and closer muscle. After enough tension has been built up, a second closer muscle contracts, and the claw rapidly closes. As the claw closes, water is rapidly displaced from the socket, and a high-speed water jet is formed and shoots out from the claw. Due to the high speeds of the water jet, low pressures are created in its wake. These low pressures are low enough to create cavitation. As has been observed by several research teams, a non-spherical cavitation bubble, elongated in the direction of the water jet, is formed. High-speed photography coupled with hydrophone measurements has proved that the collapse of the cavitation bubble causes the distinct snapping sound that can be heard from the shrimp. A series of high-speed photography experiments by Versluis et al. [53] helped to clarify at what stage in the claw closure process the sound was emitted. Before these results were obtained, the source of the sound was for a long time believed to be caused by physical contact of the claw parts. The noise emitted from colonies of snapping shrimp, occurring during both days and nights, can be

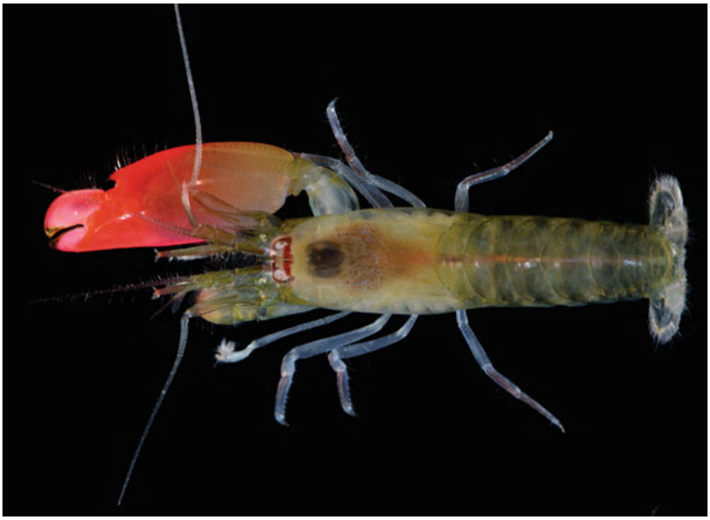

**Fig. 4.1** The body of a snapping shrimp. Note the asymmetric claw size with the right claw (on this particular individual) being much larger than the left claw, from [2]

loud enough to severely impact the use of sonar in various applications [3, 9], and researchers are currently working on techniques to mitigate snapping shrimp noise; see e.g., [23].

As the violent bubble collapse takes place, light is emitted. This was initially termed "shrimpoluminescence" by Lohse et al. [28], because it was the very first time a discovery was made that an animal produced light in this mode. The emitted light is too brief to be detected by the naked eye, and one has to use rather advanced equipment to capture and measure the intermittent light bursts. The bubble collapses and, following light emittance, produces extreme temperatures—at least 5000 K! As a side note, one can compare with the surface temperature of the sun, which is close to 5800 K.

During interspecies communication, the shrimps are located far away from each other to not get injured but close enough to receive information from the high-speed jet [16, 17]. The information is believed to be picked up by four different types of mechanosensory hairs located at the shrimp's claw because so far no auditory organs have been detected in the shrimp. Typically, shrimps face each other during interspecies communication, and most likely the information picked up by the shrimp that received a snap determines the following behavioral response such as mating, evasive maneuvers, or fighting [48]. Therefore, one could conclude that the high-speed jet is a way to communicate. Experiments on different types of snapping shrimp have shown that jet velocity, distance, and width depend largely upon shrimp size and sex [16].

**Fig. 4.2** Mantis shrimp with a white arrow pointing at its club-like claw used to stun or kill prey. Credit: Roy L. Caldwell, Department of Integrative Biology, University of California, Berkeley, Courtesy: National Science Foundation

## 4.3 A Deadly Punch

Another sea creature with an amazing ability is the Mantis shrimp (Stomatopoda), shown in Fig. 4.2. Mantis shrimp can grow to be as long as 0.38 m, and some groups of Mantis shrimp are equipped with a club-like claw that can deliver powerful high-speed blows to kill or stun prey. But, the Mantis shrimp also uses their club-like claws for more practical purposes such as to excavate their burrows. A clever latch mechanism lets the shrimp increase their power output to the claw and impact forces as high as 1000 N have been measured [34–36]. As the claw impacts the surface of the target, a low-pressure region is created due to the rapid displacement of water—similar to the water jet scenario created by the snapping shrimp. This in turn creates cavitation, and as the cavitation bubbles collapse near a target surface, an additional impact force is generated, which—perhaps surprisingly—can be of the same order or even higher than the first physical impact [34].

## 4.4 From a Tiny Bubble to a Supernova

The small shrimps described earlier are able to generate extreme pressures and kill their pray using collapse of cavitation bubbles. A spectacular physical phenomenon of sonoluminescence or transformation of sound into light is directly connected to a rapid collapse of small bubbles in liquid. It was first discovered accidentally at the University of Cologne in 1934 by Frenzel and Schultes [12] when they were trying to enhance the development process of photographic plates by using an ultrasound transducer in a bath with the developer liquid. When looking at the developed photographic film, they discovered small dots and realized that the dots originated from the light emitted by small bubbles as a result of acoustic field

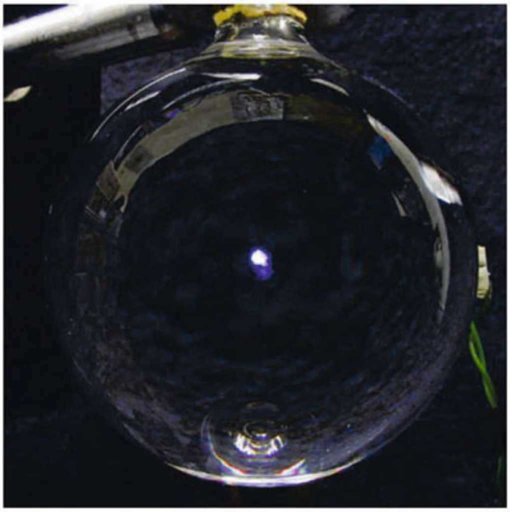

**Fig. 4.3** Photograph of a sonoluminescing bubble at the velocity node of a spherical quartz resonator; reproduced from [11], with permission from Springer

produced by a transducer in the bath. This version of sonoluminescence is often referred to as multi-bubble sonoluminescence (MBSL). The detailed experimental and numerical study of the physical processes associated with this phenomenon was initiated with the discovery of single-bubble sonoluminescence (SBSL) introduced by Gaitan and Crum [13, 14]. The authors observed pulsations of a single bubble in various glycerine and water mixtures under the load of a periodic acoustic field with frequency of 21–25 kHz. They observed short light pulses that were emitted from an oscillating bubble every acoustic period.

Figure 4.3 shows SBSL from sulphuric acid (85 wt% $H_2SO_4$ containing argon at 5% of saturation); from Flanningan and Suslick [11].

Since then a large number of researchers have studied this spectacular phenomenon both experimentally and numerically. As pointed out by Putterman [42], one of the scientists in the forefront of the sonoluminescence research, the tiny bubble caught in the node of an acoustic field serves as a lens focusing the distributed acoustic energy to energy density that produces plasma in the compressed gas within a tiny collapsing bubble. The mechanism behind this transformation is still a question of a scientific debate with many scientists attributing it to an action of an imploding spherical shock wave initiated by the motion of the imploding bubble surface acting as a spherical piston. The shock wave itself has not been detected experimentally so far. This is not so surprising keeping in mind the picosecond temporal and micrometer spatial scales of this phenomenon occurring inside a vessel filled with liquid. However, the mechanism of bubble collapse in terms of the variation of bubble radius under the action of an acoustic field is generally understood and described on the basis of experimental as well as numerical studies. A typical cycle of radius variation with time for a sonoluminescing bubble is shown in Fig. 4.4.

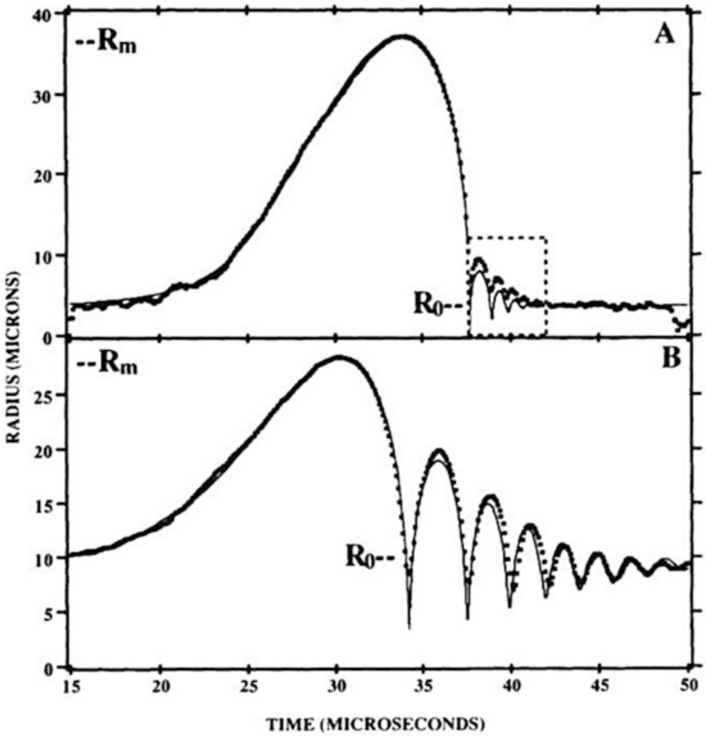


**Fig. 4.4** Radius as function of time for a sonoluminescing bubble; reproduced from [4], with permission from APS

Figure 4.4 A shows experimental data and numerical curves of bubble radius variation during a full cycle of a driving acoustic field and B the afterbounces. The numerical modeling is done by solving the Rayleigh-Plesset equation describing the evolution of a radius, $R$, of a spherical bubble under the forcing of an acoustic field [5, 27, 33, 39, 40, 44],

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left(P_g(R) - P_0 - P_a(0,t)\right) - \frac{4\eta\dot{R}}{\rho R} - \frac{2\sigma}{\rho R} + \frac{R}{\rho c}\frac{d}{dt}\left(P_g - P_a\right) \tag{4.1}$$

with the left-hand of the equation representing the bubble inertia responding to the outer forcing described in the right-hand of the equation including the forcing due to the pressure difference, viscosity, surface tension and radiation of sound. The periodic acoustic pressure field is given by $P_a = P'_a \sin \omega_a t$ and $P_g$ given by van der Waals adiabatic equation of state

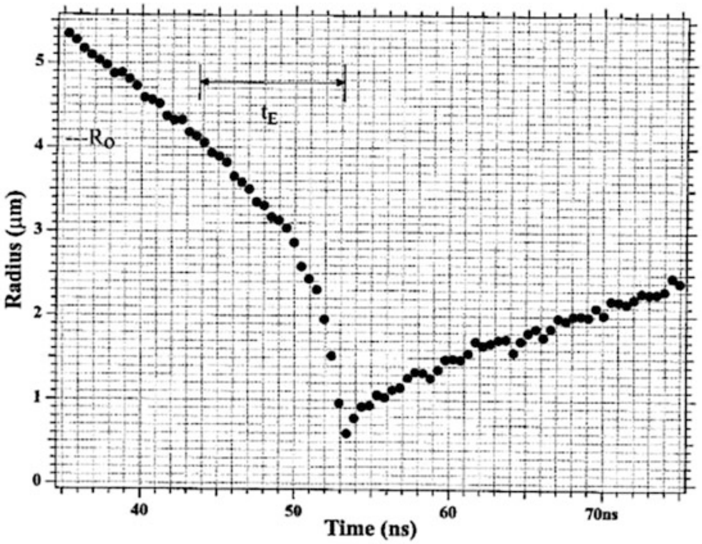


**Fig. 4.5** Radius of the sonoluminescing bubble as it collapsed towards van der Waals core; reproduced from [6], with permission from Elsevier

$$P_g = \frac{P_0 R_0^{3\gamma}}{\left(R^3 - a^3\right)^\gamma} \tag{4.2}$$

with $\gamma$ being the ratio of specific heats and $a$ the hard core radius of the bubble contents related to van der Waals excluded volume [6].

Figure 4.4 shows a typical evolution of the bubble radius during one cycle of a driving frequency. The bubble of initial radius of $R_0 = 4.5\,\mu$m expands during the negative phase of the driving pressure to approximately ten times larger bubble at an instant when the driving pressure is again positive. The pressure inside the expanded bubble is now 1000 times less than the original pressure due to the volume increase by the same amount. This enormous pressure difference functions as a driver gas in a shock tube and initiates the bubble collapse until the bubble radius approaches the van der Waals hard core being approximately one tenth of the initial bubble radius [42].

Figure 4.5 shows experimental data describing the final stage of the sonoluminescing bubble collapse as it approaches the hard van der Waals core. The speed of bubble collapse reaches four times the ambient speed of sound in gas at this stage and acceleration at the rebound from the minimum radius is of order of $3 \cdot 10^{11}$ g [42]. The extreme conditions of the compressed gas inside the collapsing bubble result in light emission from the heated gas. The duration of the light emission is estimated from 30 to 200 ps depending on the content of the gas inside the bubble, with shorter pulses for degassed air and longer for xenon bubbles in cold water [15, 19, 42].

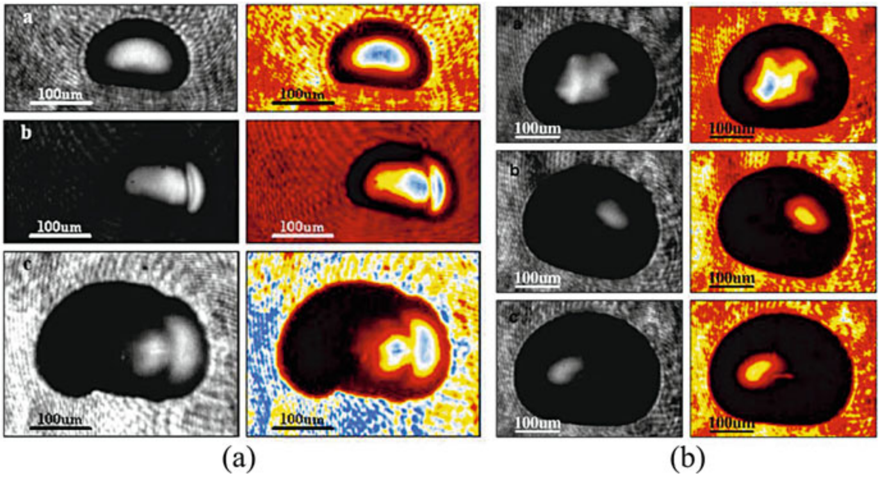


**Fig. 4.6** (**a**) Images before and after laser heating of a bright bubble and (**b**) laser beam interaction with a dim bubble; reproduced from [21], with permission from APS

So how hot is the compressed gas content in the sonoluminescing bubble? It is generally accepted that the temperature is high enough to form plasma with light emission that stems from accelerated electrons [18, 52, 54]. The degree of ionization and opacity of plasma content is still a question of discussion, and as pointed out by Khalid et al. [21], the fact that the emission spectrum of luminescing bubble is best fit by Planck's blackbody curve suggests that the source is an opaque blackbody rather than bremsstrahlung from transparent plasma. Khalid et al. present experimental investigation of the dynamic response of microplasma in a sonoluminescing bubble to a laser pulse. The researchers subjected the sonoluminescing bubble to a 3 ns-long laser pulse and compared the laser absorption in the bright and dim phases of the bubble and argue that the bright sonoluminescing bubble has high intrinsic opacity [21].

Figure 4.6 show beautiful images obtained by the researchers of the interaction of bright and dim sonoluminescing bubble with a laser pulse. Figure 4.6a shows interaction with a bright bubble before and 60 and 360 ns after laser heating which is seen in the right part of the bubble. The authors argue that the bright sonoluminescing plasma has a high degree of opacity involving strong Coulomb interactions and estimate the internal temperature to $T = (10\,500 \pm 500)$ K with a $(19 \pm 4)$ % degree of ionization. All these spectacular properties of the sonoluminescing bubble make a good reason for the "star in a jar" name used by Putterman [41].

When it comes to real stars, supernova explosions following the collapse of massive stars at the end of their life cycle give an example of most powerful energy bursts known to humanity. Supernova explosions have been observed by the astronomers through our history as very bright new stars suddenly appearing in

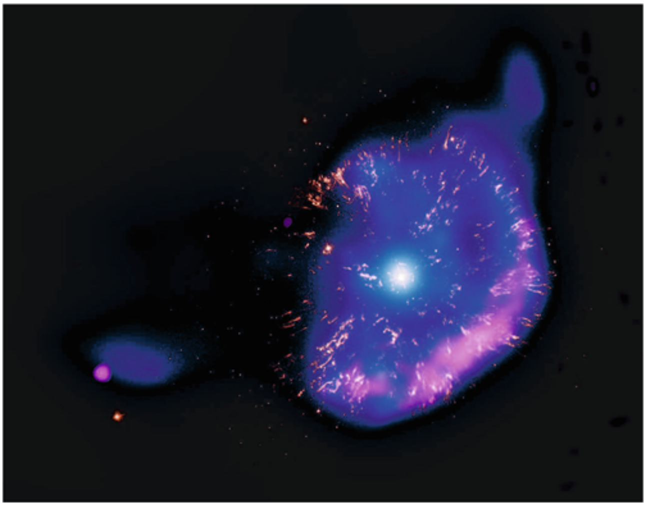

**Fig. 4.7** A "classical nova" as a miniature version of a supernova explosion; reproduced from [50], with permission from IOP

a spot where no star was detected previously. What is even more spectacular is that the brightness of the new star may increase by a factor of million times in a matter of a few hours.

Figure 4.7 shows a NASA image of a so-called "classical nova" explosion with a different mechanism of explosion from that of a supernova when the white dwarf collects mass from an orbiting companion star by gravitational pull. When enough hydrogen gas is accumulated, a nuclear fusion reaction can be ignited and produce an outgoing blast wave blowing the outer layers of the white dwarf into space. The current image is composed of X-rays from Chandra X-ray Observatory, NASA's space telescope in blue, optical data from NASA's Hubble space telescope in yellow, and radio data from electron emission caused by the shock [50].

No wonder that such events were recorded by astronomers and given various interpretations through our history. The present model of a star life cycle predicts that stars with masses greater than 8 Sun masses develop a core with a "Chandrasekhar" mass of 1.4 Sun masses. The inner core of a star with such mass becomes unstable, undergoes a gravitational collapse, and implodes from about a size of a planet to about a size of a city [7]. As a result of this collapse the core reaches matter densities exceeding those of an atomic nucleus. At this point, the collapse is stopped and reversed to rebound that generates a strong outgoing shock which overcomes the still imploding flow of matter and generates the supernova explosion [7]. A supernova explosion competes in brightness with that of the whole galaxy. This enormous burst of energy is estimated to radiant energy of our Sun for $10^{10}$ years. During this event a substantial amount of the mass of the star is ejected in the outer space and contains heavy elements up to uranium.

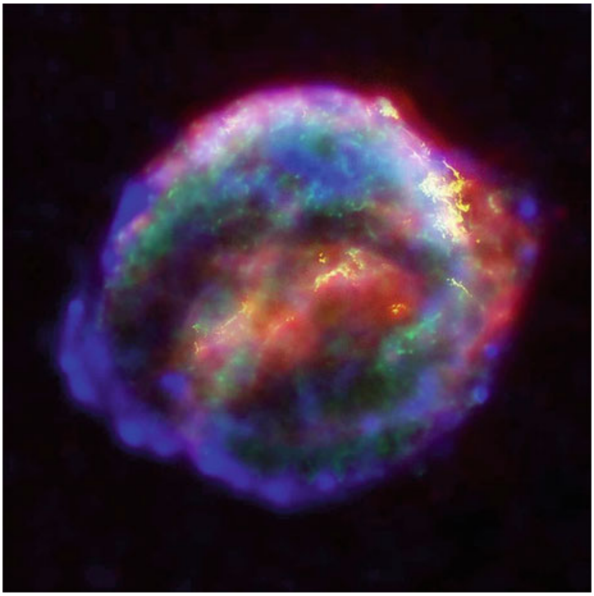

**Fig. 4.8** Kepler's supernova remnant, from NASA's Chandra X-ray Observatory, JPL, NASA

Figure 4.8 shows a NASA's Chandra X-ray Observatory image of remnants of Kepler's supernova first observed by the Chek astronomer Jan Brunowski on October 9, 1604, who reported his observation in a letter to his teacher Johannes Kepler.

## 4.5 Shock Wave Lithotripsy

A medical application of shock wave focusing is shock wave lithotripsy (SWL), which is a noninvasive treatment to eliminate kidney stones. The cost of kidney stone disease is considerable and, for example, in the year 2000 in the US alone was estimated to be close to $2.1 billion, of which the indirect cost to employers was estimated to be $775 million per year [8, 26, 29, 37, 43, 45, 46]. SWL was developed in the early 1980s and is now the primary treatment for stones in the upper urinary tract. In SWL, a lithotripter is used to generate a pressure wave and repeatedly focus it onto the kidney stone. There exist many different types of lithotripters, but they more or less function based on the same idea [31]: (1) a source to generate shock waves, (2) a method to focus the shock waves onto the desired focal region, (3) a system to localize the kidney stone so the operator knows where to aim the focal region, and (4) a medium that couples the lithotripter apparatus to the patient. Figure 4.9 shows three kinds of lithotripters.

The pressure wave that hits the kidney stone can be characterized by a leading compressive shock front followed by a long trailing tensile wave, very similar to the

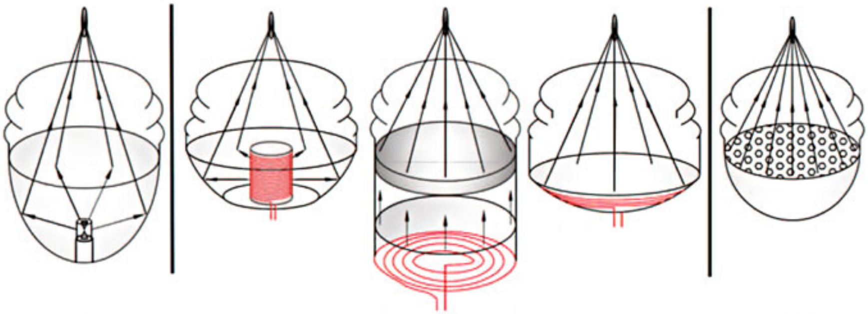


**Fig. 4.9** Examples of three different kinds of lithotripters: (**a**) electrohydraulic; (**b**) electromagnetic, which in turn shows three different types of devices, from left to right, a parabolic reflector, an acoustic lens, and a self-focusing device; and (**c**) piezoelectric; modified image reproduced from [31], with permission from Springer

pressure profile of a blast wave in a free field shown in Chap. 2. On one hand, an acoustic wave can easily be focused to an ideal focal point using an elliptic reflector. However, due to hyperbolic effects, the wave generated in the lithotripter will not focus at a point; instead, the focal point will grow to a region that increases in size with shock strength. This can be a disadvantage, as the high (or low) pressures in the area around the kidney stone can affect the surrounding tissue in a negative manner.

After many shock impacts, generally around 3000, have been delivered to the patient at a rate of about 2 Hz, the kidney stone is shattered to small fragments which can be passed naturally by the human body [4, 24, 25, 38]. The kidney stone is destroyed due to various mechanisms including spallation, squeezing, and cavitation [47].

This method of removing kidney stones has proven to be very attractive over the alternative method, surgical removal, because it appears to be safer and more cost-effective. However, SWL is not without adverse effects, such as hemorrhaging, vasoconstriction, and ischemia, occurring especially in young and elderly patients. Thus, during the last several decades, researchers have worked to improve lithotripsy technology, in which shock wave focusing is an important factor, to find methods to minimize tissue injury during SWL.

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