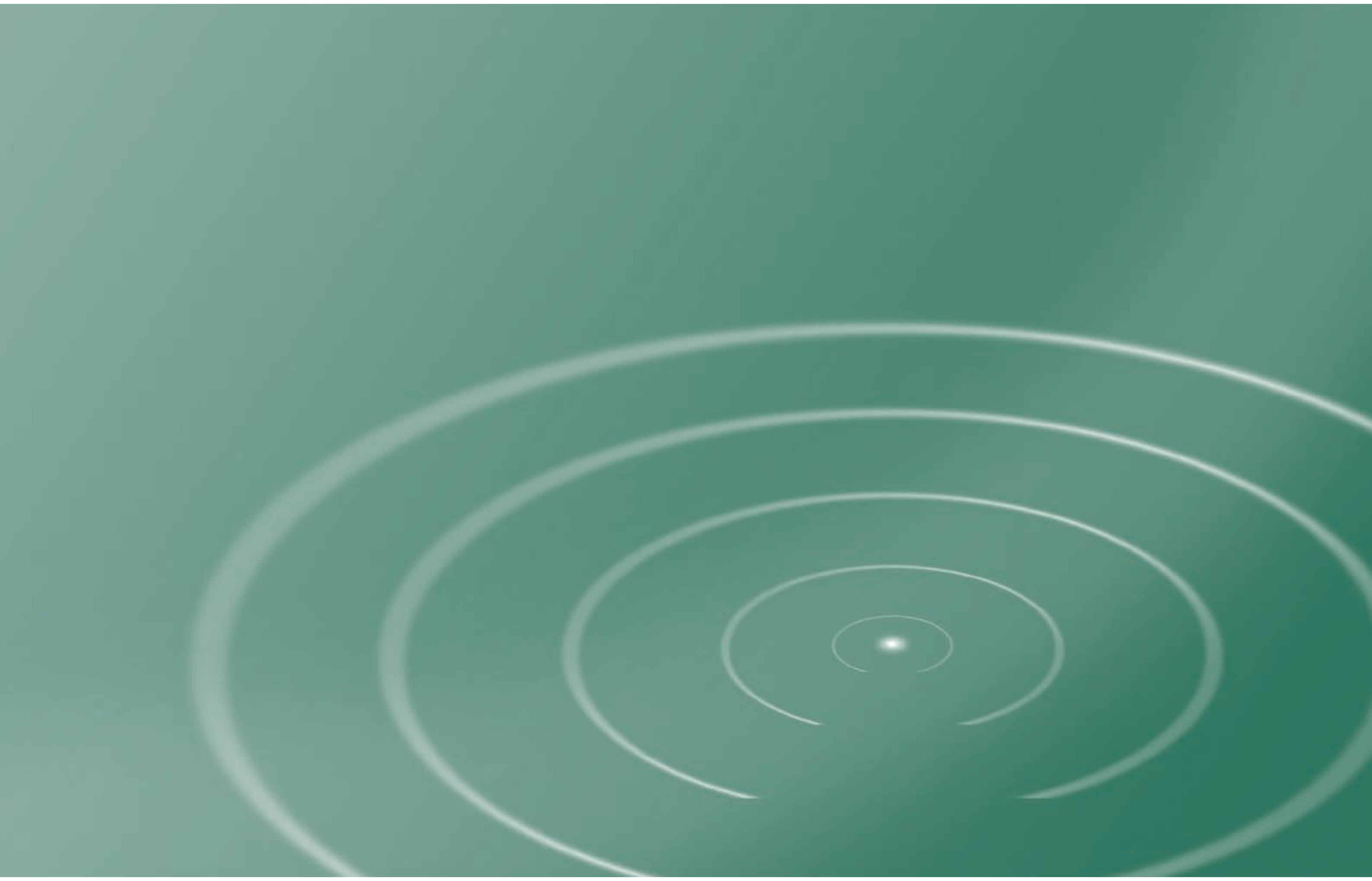
Physics and technology of shock wave and pressure wave therapy



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Physics and technology of shock wave and pressure wave therapy

Othmar Wess
STORZ MEDICAL AG, Lohstampfestrasse 8, CH-8274 Tägerwilen, Switzerland

Summary

Extracorporeally generated shock waves were first used for kidney stone fragmentation in 1980 and have since become the method of choice for most kidney and ureteral stones. More than 10 years later, shock waves were successfully utilized for the treatment of several musculoskeletal diseases. Shock waves are mechanical waves passing through the surface of a body without causing injury and may act therapeutically in predetermined areas within the body.

Shock wave generation makes use of different principles, one of them is the electromagnetic system. They are focused using acoustic lenses or reflectors. Important parameters are pressure, energy, energy flux density and different definitions for focal and treatment areas. Besides mechanical effects on acoustic interfaces, cavitation bubbles are generated which, in turn, cause needle-like punctures at interfaces. Due to both effects, fragmentation of brittle material such as kidney stones and stimulating effects such as the generation of action potentials of nerve cells take place. Biological reactions of liberation of different agents are reported. Shock waves are successfully applied to increase local blood circulation and metabolism, although the biological working mechanism is still incompletely known. Final healing is considered to be the result of these effects.

Introduction

At the end of the 1960s, the idea arose to generate shock waves in order to fragment body concrements such as kidney stones and gallstones from outside without contact. The procedure was developed by Dornier in Germany in the 1970s. With the first successful lithotripsy in a human being[1, 2, 3], this became the method of choice for almost all kidney stones and calculi in different areas of the ureter.

Kidney stones were successfully fragmented in the body of a patient using externally applied shock waves for the first time in February 1980. The mechanical energy of the shock wave was able to be transmitted to the body and exert its effect on the stone without significant damage to the tissue. The granular fragments were flushed out of the body in a natural way, eliminating the need for invasive surgery, which had been the usual procedure up to that time. This date marks the beginning of a new era characterized by the targeted application of therapeutically effective acoustic energies to human tissue. The special feature of this new form of energy in the medical field is the possibility of generating the energy outside the body and bringing it into effect on target areas deep inside the body without damaging the surrounding tissue. A new form of energy is thus available in addition to the known forms of ionising radiation for a multitude of medical applications.

After the successful fragmentation of kidney stones, the procedure was extended with varying degrees of success to stones in the gallbladder[4], in the common bile duct[5], in the pancreas[6] as well as in the salivary ducts[7, 8, 9].

The idea of using shock waves to dissolve calcifications in the shoulder[10] or at tendon insertions[11] arose. Although experts could not expect a direct fragmentation effect due to the mostly soft consistency of these calcifications compared to hard and brittle kidney stones, surprisingly the treatments were frequently successful. This demonstrated a new effect of shock waves on living tissue, namely the initiation of healing processes due to improved metabolism and increased local circulation. Today, shock waves are used to treat pseudarthrosis[12, 13], and even in cardiology to treat angina pectoris[14]. There are already indications for further areas of application, so that the potential of shock waves in medicine seems to be far from exhausted.

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In order to prevent reflection losses during application to the body, the shock wave must not be generated in air but in a medium with similar acoustic properties as those of human tissue. Generating shock waves in a water bath that is brought into contact with the patient's skin directly or via a coupling membrane is a good solution.

What are shock waves?

Shock waves appear in the atmosphere when explosive events occur, such as when explosive material detonates, when lightning strokes occur or when airplanes break the sound barrier. Shock waves are acoustic waves that are characterized by high pressure amplitudes and a steep increase in pressure in comparison to the ambient pressure. In the atmosphere, shock waves can be heard directly as loud »bangs«. They can transmit energy from the place of generation to distant areas and may cause window panes to shatter, for example.

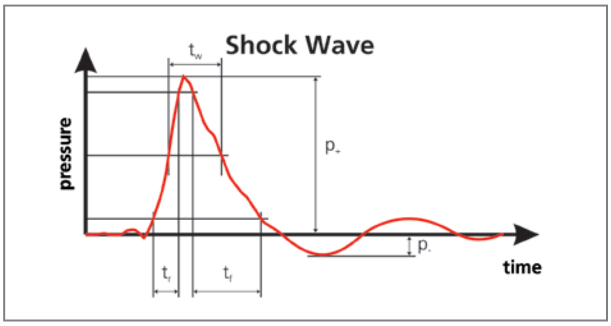

Fig. 1 – Pressure curve p(t): the rise to peak pressure (p_+) takes place in a few nanoseconds (ns). The peak pressures reach values of approx. 10 – 150 megapascals (MPa). The pulse lasts approx. 0.3 – 0.5 µs. The relatively low tensile wave component (p_-), which is limited to approx. 10% of the peak pressure, is characteristic.

Despite their relationship to ultrasound, shock waves basically differ by having especially large pressure amplitudes. For this reason, steepening effects due to non-linearities in the propagation medium (water, human tissue) have to be taken into consideration. In addition, ultrasound usually consists of periodic oscillations with limited bandwidth, whereas shock waves are represented by a single, mainly positive pressure pulse that is followed by comparatively small tensile wave components. Such a pulse contains frequencies ranging from a few kilohertz to over 10 megahertz.

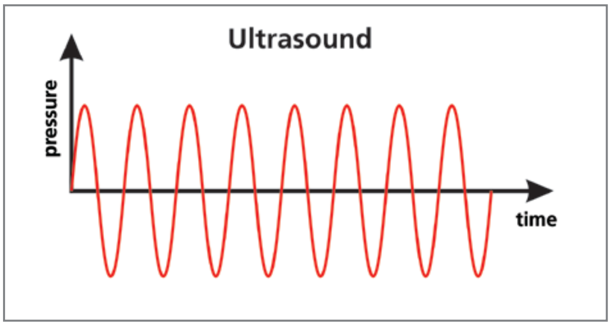

Fig. 2 – Ultrasound wave: in comparison to shock waves, ultrasound is represented by a periodic oscillation.

Methods of shock wave generation

Electromagnetic shock wave generation

The method of electromagnetic shock wave generation is based on the physical principle of electromagnetic induction, as used for example in loudspeakers. The arrangement of coils and membranes is optimized to generate powerful and short acoustic pulses.

The cylindrical arrangement of the coil primarily generates a divergent cylindrical wave, which is transformed into a convergent spherical wave using a special rotation paraboloid. It is possible to design reflectors with large diameters and great focal depth which focus the primarily generated pressure waves on the treatment zone in a highly efficient way (Fig. 3). The shock wave field of an electromagnetic cylinder source is shown in Fig. 4.

Fig. 3 – Cylindrical source with parabolic reflector: a coil is wound around a hollow cylinder and covered with an insulating layer and a conductive membrane. An electric shock generates repellent electromagnetic forces that radiate a cylindrical pressure wave at right angles to the cylinder axis, according to the geometry of the arrangement. The wave is transformed into a convergent spherical wave through reflection on the paraboloid reflector and is concentrated in the treatment zone.

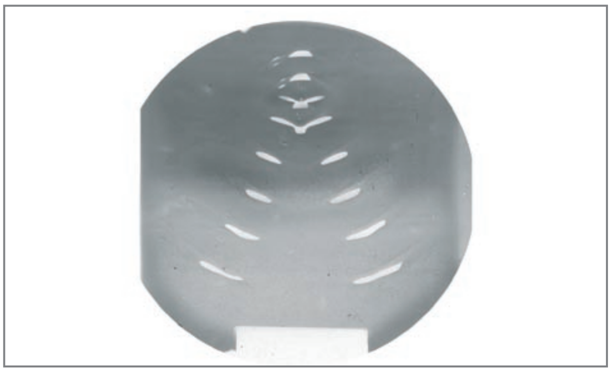

Fig. 4 – Picture series of schlieren photos of the cylinder shock wave: schlieren photograph of the fronts of successive waves on the way from the reflector to the treatment zone.

Due to the large aperture and the large aperture angle, the shock wave energy can be distributed over a large surface area of the body with little pain and can be precisely focused on the focal zone inside the body at the same time. In addition, this enables easy technical integration of »in-line« localization devices such as ultrasound transducers or X-ray systems on the axis of the shock wave head in order to ensure high-precision treatment of target areas deep in the tissue.

In physical terms, electromagnetically generated shock waves are not produced in the focal zone until the pressure amplitudes have become so high that steepening effects are activated by non-linear propagation. The steepening of a wave into a shock wave is shown in Fig. 5.

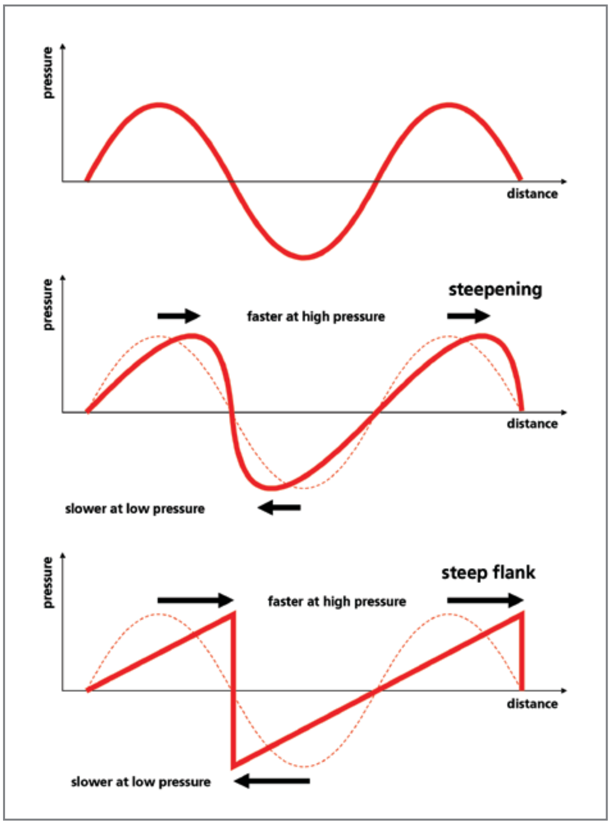

Fig. 5 – Steepening wave front due to non-linear propagation: schematic representation of the steepening of a wave front due to non-linearities in the propagation medium. The wave runs faster in zones with higher pressure and thereby steepens to form a shock wave front.

In the past few years, a trend towards electromagnetic generation methods has become apparent compared to alternative shock wave generation methods. Electromagnetic generators reduce service requirements and also allow precise and gentle dosing of the applied shock wave energy.

Propagation of shock waves (reflection, refraction and scatter)

Shock waves, similarly to any other type of acoustic wave, require a medium for propagation. Medically used shock waves are generally generated in water and become effective in biological tissue. The pressure is transmitted through the displacement of mass particles, as shown in Fig. 6.

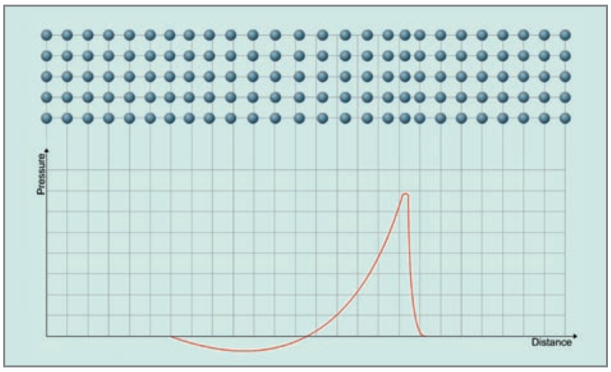

Fig. 6 – Shock wave propagation: propagation of a shock wave (schematic) through displacement of particles from the rest position and their springing back to rest position. The negative pressure component of the wave is caused by particles that overshoot.

The water bath is important for medical application of shock waves because the passage to body tissue takes place without any significant change in the acoustic impedance. Acoustic interfaces at which the acoustic properties of density (ρ) and sound velocity (c) change produce a deviation from the straight propagation of waves as known from optical phenomena such as refraction, reflection, scatter and diffraction. These effects must be taken into consideration when applying shock waves to human beings, in order to ensure that the energy can become effective in the treatment zone. On the other hand, these properties of shock waves can be used systematically to focus and locally release energy in specific areas of the body.

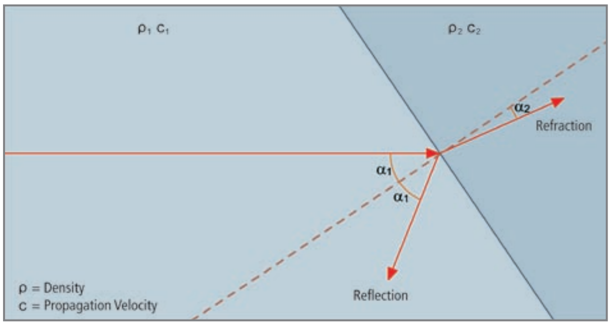

Fig. 7 – Refraction at an interface: reflection and refraction of shock waves at interfaces with different acoustic impedance (density ρ x sound velocity c).

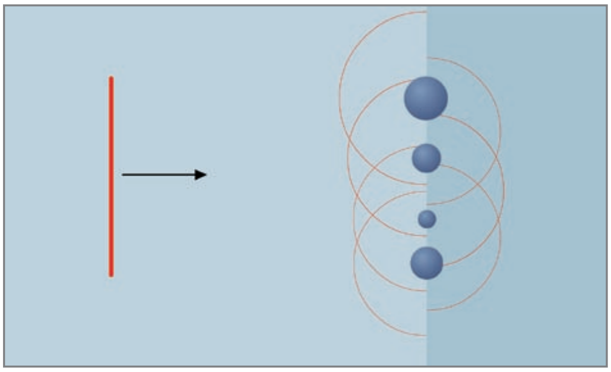

Fig. 8 – Scatter: shock waves are scattered by obstacles such as rib bones and gas bubbles.

As previously mentioned, the generation of shock waves in a water bath or a tissue-like medium is decisive to avoid a significant loss of energy through reflection when the shock waves are introduced into the body. The first device for kidney stone fragmentation required the patient to be submerged in a water-filled tub. Today's devices work with the so-called »dry« coupling, which means that the water bath is connected to the body via a flexible diaphragm. An air film in between is eliminated with coupling-gel or a thin water film. Regardless of this, it must be ensured that no gas-filled organs (lungs) or large bone structures are located in front of the treatment area. These would act as obstacles on the shock wave propagation path to the target zone and thus prevent the desired therapeutic effect.

It must also be assumed that soft tissues (skin, fat, muscles, tendons, etc.) are not acoustically homogeneous or without interfaces. However, the differences in the acoustic properties are considerably less than at the boundaries between water and air. In addition to absorption and reflection, refraction effects occur here which may lead to difficult-to-control deviations from the straight propagation path of shock waves in the body.

Shock wave parameters/measurement of shock waves

Shock wave pressure

Shock waves are mainly characterized by means of measurements with pressure sensors[15]. This requires a very small sensor with a high load capacity and wide frequency response. As shown in Fig. 9, the measurement of a shock wave field consists of a multitude of point measurements at different positions in the shock wave field.

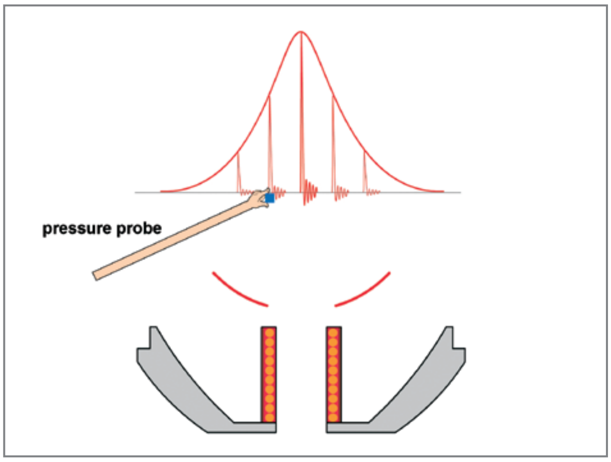

Fig. 9 – Pressure sensor in the shock wave field: shock wave fields are measured with a pressure sensor by recording the pressure curves at different positions within the field. All other parameters are calculated from the pressure values plotted over time.

In each measurement, the peak pressure p_+ as well as the pressure profile over time with rise time t_r, pulse duration t_w, tensile phase p_- etc. are measured (see Fig. 1). Shock waves used in medicine show typical pressure values of approx. 10 – 100 megapascals (MPa) for the peak pressure p_+. This is equivalent to 100 – 1000 times the atmospheric pressure. The rise times t_r are very short at around < 10 – 100 nanoseconds (ns), depending on the type of generation. The pulse duration t_w of approx. 0.3 – 0.5 microseconds (µs) is also quite short (in comparison to the medically used pressure waves described further below). Another characteristic of shock waves is the relatively low tensile wave component p_-, which is around 10% of the peak pressure p_+.

Other parameters of the shock wave field are calculated from this data in a rather complex procedure. If the peak pressure p_+ values measured at various positions in the shock wave field are plotted in a three-dimensional representation (coaxially to the shock wave propagation path and vertically to this direction), a typical pressure distribution chart as the one shown in Fig. 10 results.

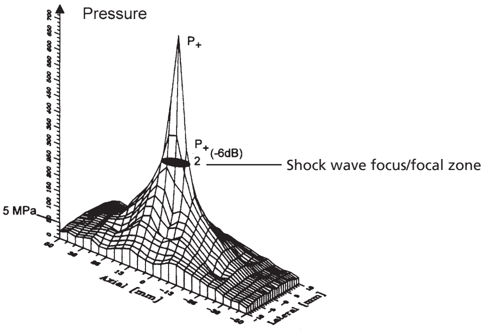

Fig. 10 – Pressure distribution in the x/z plane: pressure distribution in a plane of the shock wave field, axially in the direction of shock wave propagation and laterally to this direction. The peak value p_+ measured in the respective position in the shock wave field is plotted on the y axis.

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[15] Wess, O.; Ueberle, F.; Dührssen, R. N.; Hilcken, D.; Krauss, W.; Reuner, Th.; Schultheiss, R.; Staudenraus, I.; Rattner, M.; Haaks, W.; Granz, B.: Working Group Technical Developments – Consensus Report. In: Chaussy, C., Eisenberger, F., Jocham, D., Wilbert, D. (eds.) High Energy Shock Waves in Medicine. Georg Thieme Verlag, Stuttgart 1997

Obviously shock wave fields do not have sharp boundaries, but the shape of a mountain with a peak in the centre and more or less steeply falling slopes. This phenomenon is referred to as pressure distribution. Different shock wave devices differ in the shape and height of this three-dimensional pressure distribution graph, for example.

-6 dB shock wave focus

For the selective treatment of locally confined areas in deeper tissue layers (pseudarthrosis, femoral head necroses, kidney stones …), shock waves are bundled in order to limit the desired effects to the target area. The highest pressure values are measured in the compression zone. If the pressure sensor is moved away from the centre of compression, the pressure values continually decrease. As a result of the physical characteristics, it is not possible to draw a sharp boundary beyond which pressures abruptly fall to zero. For this reason, it is not possible to sharply define the effective zone of the shock waves with a fixed spatial contour. Physically, the focal zone is defined as the area of a shock wave field in which the measured pressures are greater than or equal to half the peak pressure measured in the centre (Fig. 11).

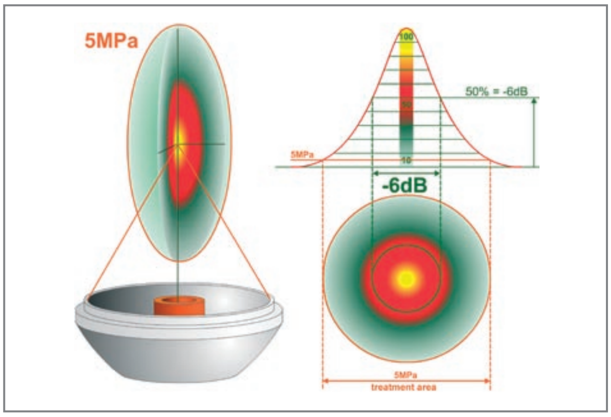

Fig. 11 – -6 dB focus, 5 MPa focus: representation of the -6 dB focus (defined by the area above half the peak pressure, ½ p_+) and the 5 MPa focus (defined by peak pressures $p > 5$ MPa)

The area defined in this way is also referred to as -6 dB focus zone or described using the abbreviation FWHM (Full Width at Half Maximum). This is a spatial area that relates to the peak pressure, which, however, does not initially provide any information on the energy it contains or on the biological effect.

5 MPa treatment zone

It is only by adding information on the energy level that it is possible to give an impression of the area in which the shock wave will unfold its biological effect. In other words: the shock wave treatment area in the body is not described by the size of the (-6 dB) focus. It can be larger or smaller. As a result, an additional value has been defined that is more closely related to the therapeutic effect and is not based on relative quantities (relationship to the peak pressure in the centre) but on an absolute quantity, namely the pressure of 5 MPa (50 bar). Consequently, the 5 MPa focus[15] has been defined as the spatial zone in which the shock wave pressure is greater than or equal to 5 MPa. If a certain pressure limit is assumed to exist, below which shock waves have no or only minimal therapeutic effect, this is taken as a measure and, somewhat arbitrarily, assumed to be 5 MPa. Even if this value has to be corrected in the future according to the indication to be treated, this definition offers the advantage of reflecting the change in the treatment zone with the selected energy setting.

The different zones and their changes according to the selected energy levels are schematically represented in Fig. 12.

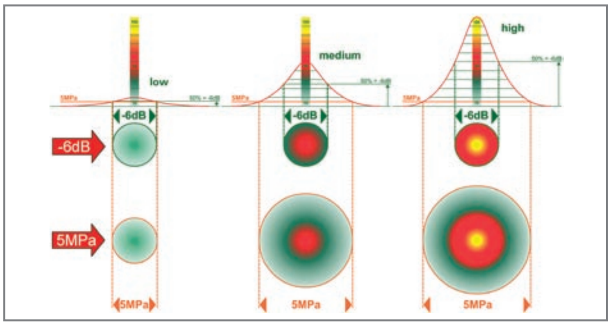

Fig. 12 – -6 dB focus vs. 5 MPa treatment zone at different energy settings: -6 dB focus in comparison to the 5 MPa treatment zone with different energy settings: low, medium and high. Despite the different energy contents, the dimensions of the (-6 dB) focus remain almost unchanged. The 5 MPa treatment focus increases with the energy level and thus demonstrates the extended activity area of the shock waves.

In this example, it can be seen that the -6 dB focal zone does not become larger or smaller despite different energy settings. When the energy increases, however, it can be assumed that the effective zone of the shock waves will increase in size. This is expressed in the increasing size of the 5 MPa zone.

Energy (E)

The energy of the applied shock waves is an important parameter for practical applications[15]. It can be assumed that shock waves only have an effect on tissue when certain energy thresholds are exceeded. In addition to the time curve of the shock waves p(t) (see Fig. 1), the surface area A in which the pressure is effective is also decisive. Using the acoustic density (ρ) and sound velocity (c) parameters of the propagation medium, the following energy equation is obtained:

$$\mathbf{E = A/\rho c \int p(t)dt}$$

A distinction is made as to whether integrating the pressure over time only includes the positive pressure components (E_+) or whether it also covers the negative (tensile) components (E_{total}). The total energy is usually given with E (without index). The acoustic energy of a shock wave pulse is given in millijoules (mJ). As a rule, several hundreds or thousands of shock wave pulses are emitted per treatment, so that the total energy applied is obtained by multiplication by the number of pulses.

Energy flux density (ED)

As previously mentioned, the therapeutic effect of shock waves depends on whether the shock wave energy is distributed over a large area or concentrated on a locally confined treatment zone. A measure of the energy concentration is obtained by calculating the energy per area (E/A).

$$\mathbf{E/A = 1/\rho c \int p(t)dt = ED\ (energy\ flux\ density)}$$

The energy flux density ED is given in millijoules per square millimetre (mJ/mm^2). Here again, one distinguishes between integration over the positive part of the pressure curve alone on the one hand and inclusion of the negative part on the other hand[15]. Without index (ED), the pressure curve is usually considered to include the negative (tensile) components (total energy flux density).

The effect of the focusing on the energy flux density is schematically represented in Fig. 13.

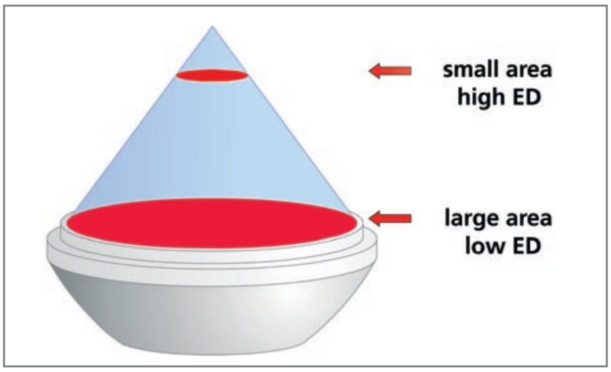

Fig. 13 – Focusing with ED low vs. ED high: with the same total energy, the energy flux density increases with focusing. Reducing the area concentrates the energy and thus increases the effect of the shock waves.

The above parameters are usually sufficient to characterize a shock wave field for medical applications. Shock wave devices that work with different generation principles can differ in relation to the listed parameters. The »quality« of the shock waves used in the treatment zone should be independent of the generation principle, however. In other words: the measurement of the above parameters in the treatment zone does not allow any fundamental conclusions to be drawn about the type of generation. The principles of shock wave generation differ with respect to secondary parameters such as repeat accuracy, dosage, energy range, operating costs for consumables, durability of source etc.

It should be added that the above parameters are usually measured in water. Due to the inhomogeneities in tissue, however, deviations from the straight propagation of shock waves lead to a spatial expansion of the focal zones. With increasing depth in the body, the peak pressure as well as the energy flux density will therefore decrease compared to a measurement in a water bath.

Physical effects of shock waves

Direct effect on interfaces

Shock waves have different characteristics as compared to ultrasound. Ultrasound exerts a high-frequency alternating load on the tissue in the frequency range of several megahertz, which leads to heating, tissue tears and cavitation at high amplitudes. One factor determining the effect of shock waves is the forward-directed momentum (in the direction of the shock wave propagation). A force acts at the interface that can be increased up to the destruction of kidney stones.

Since these dynamic effects basically occur at interfaces with a jump in the acoustic resistance, but hardly ever in homogeneous media (tissue, water), shock waves are the ideal means for creating effects in deep tissue without interfering with the tissue in front of it. However, even less distinct interfaces within soft tissue structures experience a small momentum from shock waves. Topics of discussion include the mechanical destruction of cells, membranes and bone trabeculae[16], for example, as well as the stimulation of cells through reversible deformation of the cell membrane[17]. As long as the treated areas are not on the skin surface, focusing also leads to an increased effectiveness in the treatment area while simultaneously reducing side effects outside this area.

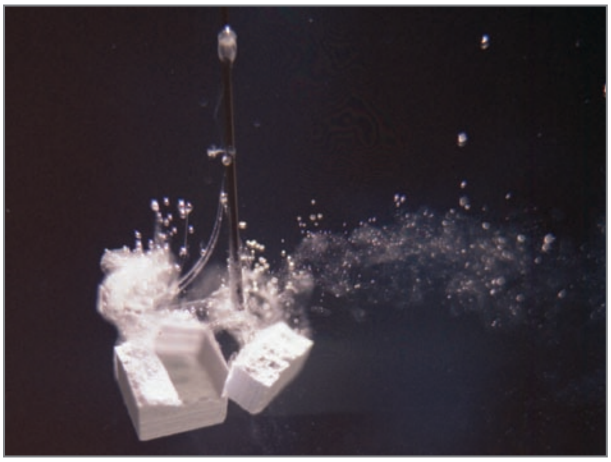

Fig. 14 – Stones with separation of fragments: effect of a focused shock wave on a cube-shaped artificial stone with an edge length of 10 mm (shock wave occurrence from the right). One can see the stone held on a wire, the fragmentation into a few concrements and cavitation bubbles in the shock wave path.

This produces very different effects on the tissue, which lead to a primary destruction of brittle structures (kidney stones) or to irritation and healing processes through stimulation, which can be observed in orthopaedic applications in particular. As a consequence of shock wave therapy, increased local blood circulation and enhanced metabolism can usually be observed, to which the resulting healing process can be attributed.

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Indirect effect

Cavitation

In addition to the direct dynamic effect of shock waves on interfaces, so-called cavitation occurs in certain media such as water and sometimes in tissue as well[18]. Cavitation bubbles occur directly after the pressure/tension alternating load of the shock waves has passed the medium. A large number of bubbles grow until approx. 100 microseconds after the waves have passed and then violently collapse while emitting secondary spherical shock waves (Fig. 15).

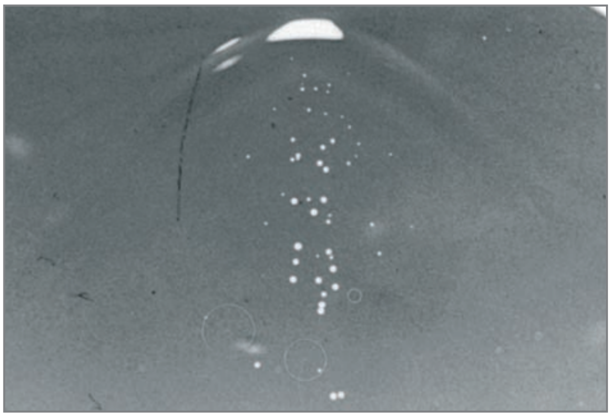

Fig. 15 – Cavitation bubbles behind the shock wave front with secondary spherical shock waves: cavitation bubbles created by a shock wave running from bottom to top. Directly behind the shock wave, the bubbles are still small. They grow within approx. 30 microseconds and then collapse while emitting a secondary (spherical) shock wave (circular rings at the bottom of the frame).

Near interfaces, cavitation bubbles can no longer collapse without being disturbed. The medium flowing back into the bubble (water, body fluid) can no longer flow unhindered, and the bubble therefore collapses asymmetrically while developing a micro-jet[19]. As shown in Fig. 16, this micro-jet is directed at the interface with speeds of several hundred metres per second.

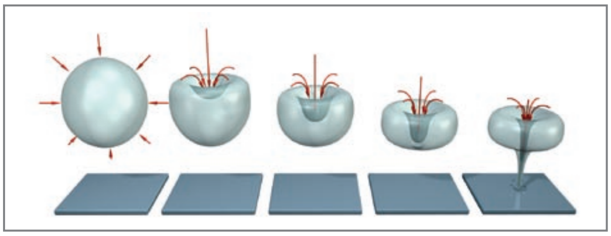

Fig. 16 – Creation of a micro-jet: cavitation bubbles near obstacles cannot collapse in a spherically symmetrical way, since the obstacle hampers the flow of the fluid. This causes the development of micro-jets that hit the interface at several hundred metres per second and lead to erosion or punch needle-like holes in vessels or membranes (schematic).

The micro-jets contain a high amount of energy and penetration power so that they not only erode the hard interfaces of stones but can also penetrate the walls of small vessels. This causes micro bleeding or membrane perforations. Cavitation is not limited to the focal zone, but is especially pronounced there. Cavitation is another biologically effective mechanism produced by shock waves, which can be selectively used in localized areas, even in deeper tissue layers. The physically induced energy can cause biological reactions via different mechanisms.

Frequently, these reactions initially lead to improved local blood circulation and then activate repair mechanisms as a result. In addition to the direct mechanical effects in tissue, stimulation effects can also be detected in the nervous system, which may correct pathological reflex patterns and thus lead to long-term recovery[20].

Selective application of localized shock waves

Technical equipment for shock wave application is supplied with different focal distances, depending on the penetration depth. For applications over a depth of several centimetres, the system must usually be equipped with a localization device. An X-ray or ultrasound localization device is used, depending on

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the indication. The treatment area is displayed using one of the common imaging methods and brought into line with the treatment zone of the shock wave device via corresponding adjustment. Shock wave systems are offered with very different localization features in terms of complexity, convenience, precision and localization modality.

If the target zones are close to the body surface, shock wave application can generally be performed without a localization device. The target area can be identified using separate ultrasound or X-ray devices and simply marked on the skin. The shock wave device is placed on these marks and treatment is then carried out. Such systems can be offered at convenient prices since they do not require an expensive built-in targeting device.

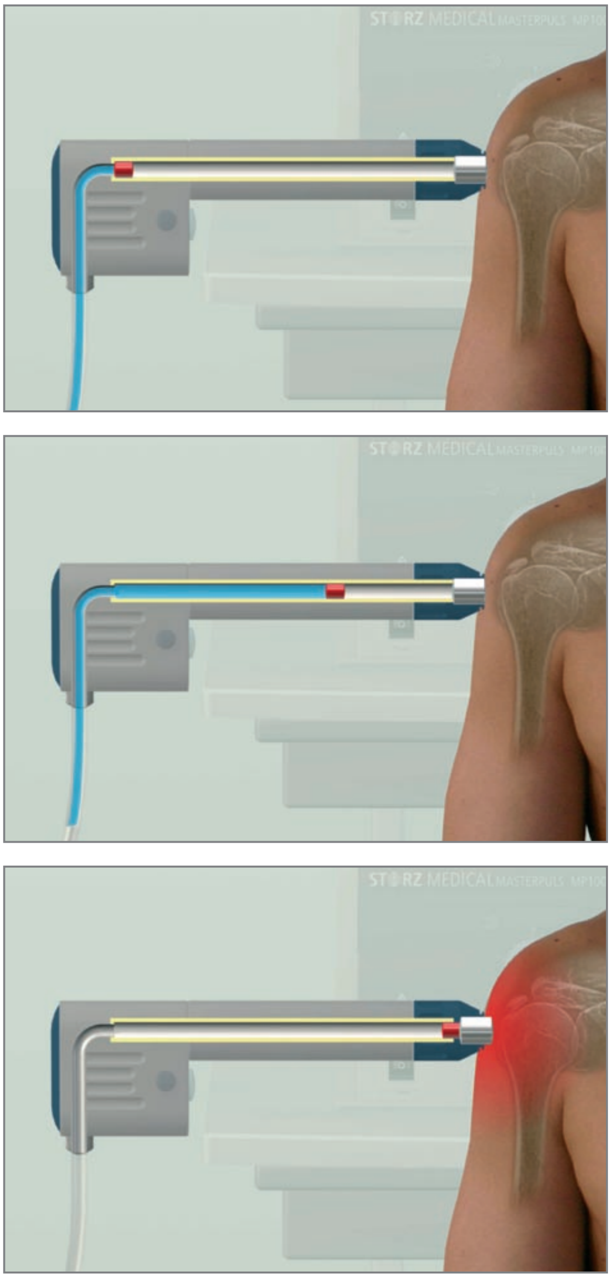
For high-precision targeted shock wave application, all deeper treatment areas require an integrated localization device that has a precise spatial relationship to the actual shock wave applicator. If the configuration of the shock wave source allows the localization device to be centrally integrated on the shock wave axis (in-line), high localization accuracy and easy-to-interpret spatial relationships will be obtained. Systems located outside the treatment head (off-line) may be operated independently with greater flexibility. The localization geometry, however, is more complex and generally not suited to directly detect obstacles in the shock wave path.

When treating patients without anaesthesia, it is often possible to identify the point of maximum pain through simple communication with the patient. This procedure is called »bio-feedback« and it is used to find superficial and deeper treatment points without requiring an expensive localization device.

Generation of pressure waves

In addition to the focused shock waves described above, pressure waves with different features are used in modern medicine today. Whereas shock waves typically travel with the propagation speed of the medium (approx. 1500 m/s for soft tissue), pressure waves are usually generated by the collision of solid bodies with an impact speed of a few metres per second (approx. 5 – 20 m/s), far below the sound velocity. First of all, a projectile is accelerated, e.g. with compressed air (similarly to an air gun), to a speed of several metres per second and then abruptly slowed down by hitting an impact body. The elastically suspended impact body is brought into immediate contact with the surface of the patient above the area to be treated, using preferably coupling gel, if necessary. When the projectile strikes the impact body, part of its kinetic energy is transferred to the impact body, which also makes a translational movement over a short distance (typically < 1 mm) at a speed of around one metre per second (typically < 1 m/s) until the coupled tissue or the applicator decelerates the movement of the impact body.

The motion of the impact body is transferred to the tissue at the point of contact, from where it propagates divergently as a »radial« pressure wave.



Figs. 17,18,19 – Phases of pressure wave generation through the impact of solid bodies on an impact body (transmitter). The impact body transmits the pressure pulse to the coupled tissue. Fig. 17 – Projectile at rest. Fig. 18 – Acceleration of the projectile. Fig. 19 – Projectile strikes the impact body and sends a pressure wave into the body

The time duration of the pressure pulse is determined by the translational movement of the impact body and typically lasts approx. 0.2 – 2 milliseconds in tissue.

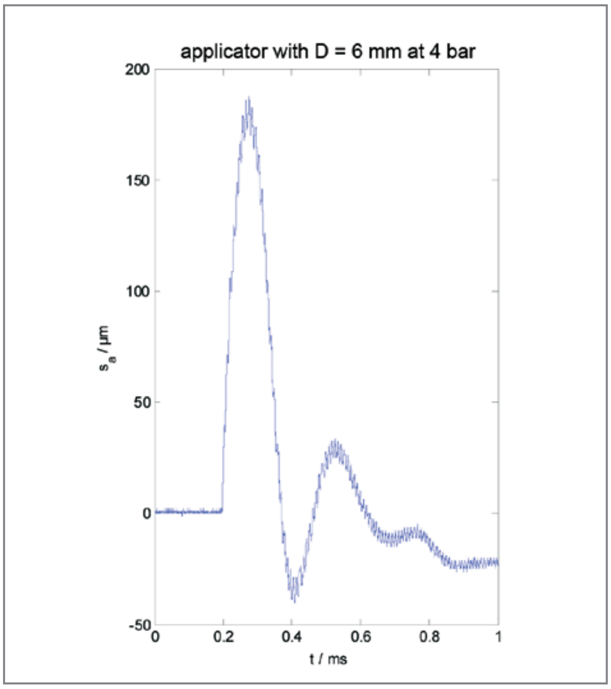


Fig. 20 – The excursion of an impact body after collision with a striking body in the air. The impact body is displaced by approx. 0.2 millimetres (mm) within a period of approx. 0.2 milliseconds (ms).

To simulate the conditions found when the pressure disturbance is induced into the body, the displacement of the impact plate can be examined when in contact with water. The time profile of the displacement is damped by the coupled water (displacement approx. 0.06 mm) and slightly distorted. (Note the changed time scale).

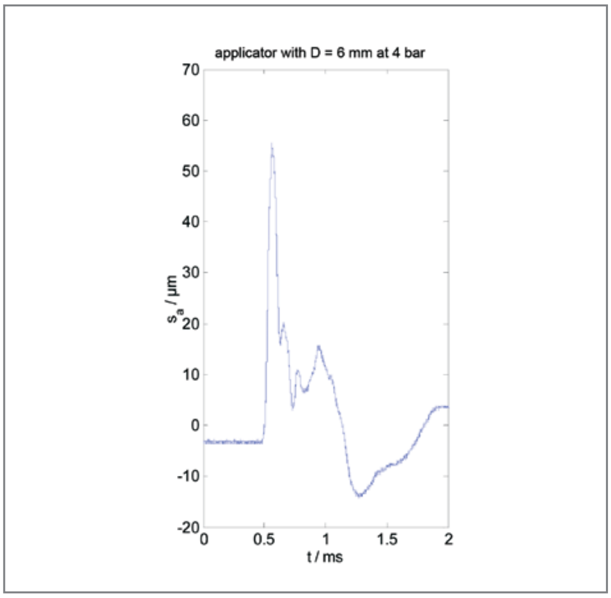


Fig. 21 – Displacement of an impact body in water: displacement of an impact body after collision with a striking body in water. The impact body is displaced approx. by 0.06 mm within a period of approx. 0.5 milliseconds. (The time scale is changed when compared to Fig. 20)

As a result of its displacement, the impact body transfers a pressure disturbance to the coupled tissue, which shows the same time behaviour at the contact point as the displacement. The pressure pulses transferred to the tissue thus have a duration of 0.5 ms and are longer than the above-described shock waves by a factor of approx. 1000. At approx. 0 – 10 MPa, typical peak pressures with this method are lower by a factor of > 10.

The extremely long pulse duration in comparison to shock waves has a decisive influence on the propagation of pressure waves in tissue. Unlike shock waves, such pressure waves cannot be focused on narrow tissue areas. In relation to the size of the human body, focusing cannot be achieved for physical reasons[21].

A detailed observation of the collision process between the projectile and the impact plate, however, shows a further phenomenon that can be seen in the jagged shape of the curve in Fig. 20 and to a lesser extent in Fig. 21.

The projectile and the impact body placed against the body are generally made of metal. When the two metal bodies collide, high-frequency harmonic oscillations (rod waves) are excited in the metal bodies. These oscillations are superimposed on the »slow« translational movement of the impact body. This process is illustrated in Figs. 22 – 24.

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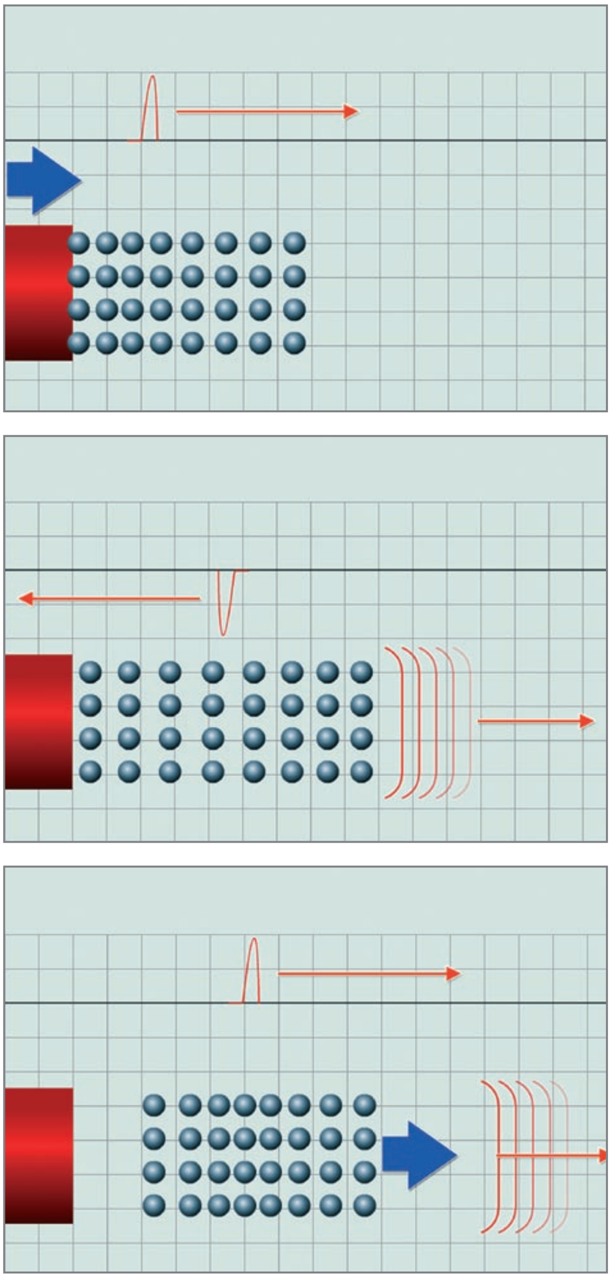
[21] Robin O. Cleveland,* Parag V. Chitnis,* and Scott R. Mcclure†: Acoustic field of a ballistic shock wave therapy device, Ultrasound in Med. & Biol., Vol. 33, No. 8, pp. 1327 – 1335, 2007



Figs. 22, 23, 24 – Generation of harmonic oscillations (rod waves) in the impact body: the displacement of the impact body is superimposed by a harmonic oscillation (rod waves) in the impact body.

22 – The projectile hits the impact body. The pressure disturbance caused by the impact passes to the distal end of the impact body and is reflected there as a tensile wave.

23 – After the pressure disturbance has passed through twice, the tensile wave returns to the collision point with the projectile at the proximal end of the impact body.

24 – Only then does the impact body detach from the projectile and move towards the coupled tissue at a speed of several metres per second. Part of the energy is already radiated into the surrounding medium at the distal end (schematic representation).

The impact of the projectile creates a pressure wave in the impact body that runs through the impact body at a propagation speed that is typical of metal (v > 2000 m/s). At the distal end of the impact body, the wave is reflected as a tensile wave and returns to the collision point with the projectile in front. The impact body does not separate from the projectile until this wave has passed through the impact body once in both directions. As described above, the impact body begins its translational movement at a speed of several metres per second. At the same time, the rod wave that is reflected as a pressure wave passes through the impact body once more and is reflected again at the distal end as in the first passage. The process is repeated several times, so that the described wave in the impact body is superimposed on the »slow« translational movement.

Due to the great differences in the acoustic impedance between the metal impact body and the coupled water or tissue, a large part of the energy of these high-frequency oscillations remains bound in the impact body. Only a small part (approx. 10%) of the oscillation energy is radiated into the water and can be picked up there using the usual hydrophones. This is a damped oscillation, as shown in Fig. 35. The pressure amplitudes show values of up to 10 MPa and are thus below the pressure values usually achieved with shock waves by a factor of approx. 10 to 100. So this is the reason why these waves are not shock waves in a physical sense.

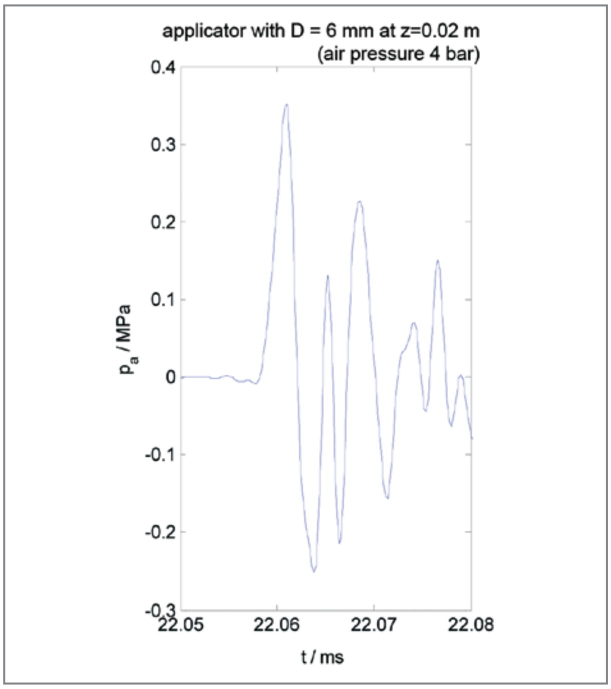


Fig. 25 – Damped oscillation of the radiated rod wave: Example of a pressure measurement at a distance of 2 mm from the place of application. Measurement of the radiated harmonic oscillation displayed schematically as in Figs. 22 – 24. Note the changed pressure scale. The damped oscillation shows a peak pressure of less than 0.4 MPa (4 bar), which is considerably lower than that of a focused shock wave.

The energy contained in the high-frequency harmonic oscillation is several orders of magnitude smaller than the energy content of the aforementioned (low-frequency) pressure pulse. It is within the range of diagnostic ultrasound. Nevertheless, it cannot be ruled out that a certain treatment effect is related to this.

The previously described pressure pulse, which is long in comparison to shock waves, is difficult or impossible to detect with the common pressure sensors used in shock wave technology.

Pressure waves as described here emanate from the application point of the impact body and travel radially into the adjacent tissue. The energy density of the induced pressure wave quickly drops with increasing distance from the application point (by a proportion of $1/r^2$), so that the strongest effect is at the application point of the applicator. One difference between focused shock waves and unfocused pressure waves is the fact that focused shock waves can be directed into deeper tissue, where they develop a therapeutic effect without causing skin lesions. Unfocused pressure waves, on the other hand, primarily have an effect on the surface.

Technical differences

The technical differences are shown below:

	Shock waves (focused)	Shock waves (planar)	Pressure waves (radial)
Focus	yes	no	no
Rise time	typically 0.01 µs	typically 0.01 µs	typically 50 µs
Compression pulse duration	approx. 0.3 µs	approx. 0.3 µs	approx. 200 – 2000 µs
Positive peak pressure	0 – 100 MPa	0 – 30 MPa	0 – 10 MPa
Energy flux density	0 – 1.5 mJ/mm² in the body	0 – 0.4 mJ/mm² at skin surface	0 – 0.3 mJ/mm² at skin surface
Therapeutic effect in body	0 – 12 cm	0 – 5.5 cm	0 – 3 cm

Shock and pressure waves not only differ in their physical characteristics and the technique used for generating them, but also in the order of magnitude of the parameters normally used in shock wave treatment.

Interestingly, the stimulation effects and therapeutic mechanisms seem to be partly similar, despite the physical differences and the resulting different application areas (on the surface and in depth respectively). However, the described pressure waves are not able to fragment hard concrements such as kidney stones deeper in the body (> 1 cm). Nevertheless, unfocused pressure waves seem to be well suited for orthopaedic indications near the surface as well as for trigger point therapy, for example[22].

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[22] Gleitz, M.: Die Bedeutung der Trigger-Stosswellentherapie in der Behandlung pseudoradikulärer Cervicobrachialgien. Abstracts 53. Jahrestagung der Vereinigung Süddeutscher Orthopäden e.V., Nr. 328, April 2005

Also, radial shock waves are used for smoothing the muscles after shock wave therapy.

Figs. 26, 27 – DUOLITH® SD1 »TOWER« and »TABLE TOP«: combination device DUOLITH® SD1 for generating and applying focused/planar shock waves and radial pressure waves.

Figs. 26, 27 show a combination device for focused shock waves and unfocused pressure waves. Depending on the indication, treatment zones several centimetres deep in the body can be treated with focused shock waves, whereas unfocused pressure waves can be applied to target areas near the surface.

Fig. 28 – MASTERPULS® MP200, radial shock wave therapy device

Discussion

Shock waves have become an indispensable part of medicine. They are a means of bringing therapeutically effective energies to locally confined areas in the body in a non-invasive way. The fact that shock waves have a selective effect on acoustic interfaces and pass through homogeneous elastic tissue without causing hardly any damage is of crucial medical importance. Tissue damage outside the treatment zone is almost completely avoided due to the possibility of concentrating energy through focusing. This significantly increases the therapeutic effects within the treatment zone, although moderate side effects (haematomas) cannot be entirely ruled out, especially when high energies are used, as in lithotripsy.

In addition to the fragmentation effect in stone treatment, the stimulating effect of shock waves on biological processes has increasingly become the centre of interest in the last few years. Although the mechanism of action for this is still widely unknown, shock waves seem to have a special therapeutic potential here.

It appears that the principle of action is so universal that a multitude of very different indications respond positively to shock wave therapy. In order to study the mechanisms of action, the shock waves used must be precisely characterized using the parameters described in the text. This is the only way to determine dosage/effect relationships and to obtain sound knowledge about the mechanism of action. However, the fact that focused shock waves and unfocused pressure waves, which have clear physical differences, show similar effects, especially in the stimulation of healing processes, suggests that both forms of energy do not exert a direct mechanical effect but rather have an impact on the senso-motoric reflex behaviour.

It seems that a reorganization of pathological reflex patterns that are anchored in memory due to the stimulating effect of shock and pressure waves cannot be ruled out[19]. This would open up a previously unknown potential for further therapeutic areas of application.

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STORZ MEDICAL

STORZ MEDICAL AG · LOHSTAMPFESTRASSE 8 · CH-8274 TÄGERWILEN
TEL. +41 (0)71 677 45 45 · FAX +41 (0)71 677 45 05
E-MAIL INFO@STORZMEDICAL.COM · WWW.STORZMEDICAL.COM

SM 18 441 E 1007/SIH