Pressure Pulse Measurements Using Optical Hydrophone Principles

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Abstract. Pressure pulses are used in extracorporeal lithotripsy, pain therapy and other medical applications. Typical lithotripter pulses reach positive pressure amplitudes of ca. 20 to more than 100 MPa and negative pressures of -5 to more than -20 MPa, depending on the focusing properties and energy settings of the source. The IEC standard 61846, which defines the acoustic parameters of pressure pulse fields, describes the properties of “Focus-” and “Field-” type hydrophones, which were originally specified as PVDF sensors. During recent years, two types of optical sensors were developed, which are based on the principle of measuring reflection changes of a laser beam at a glass-water surface: The fiber optic sensor using bare optical fibers and the “light spot” sensor using a thick glass block. Measurements with both hydrophone types were made with a low pressure transducer (p+max=3 MPa), and two electromagnetic lithotripter sources with the same total acoustic energy (E5MPa=90mJ), one with a wide focus (FWHM = 11 mm, p+max= 30 MPa) and the other with a small focus (FWHM = 3,5 mm, p+max= 83 MPa). The results show that both optical sensor types provide high pressure-time signal fidelity comparable to PVDF membrane sensors. Both optical hydrophones can serve as “Focus-” and “Field-“ hydrophones as defined in the lithotripsy measurement standard IEC 61846.

1. Development and Application of Pressure Pulse Technology
In February 1980 the first patient was relieved from his kidney stones with a pressure pulse lithotripter. During the last 30 years, extracorporeal lithotripsy has evolved and remains the standard treatment method for kidney stone patients. In 2003 70% of all German kidney stones were treated by pressure pulse lithotripsy alone, additional 15% received pressure pulses combined with other endourological treatments [1].

New applications of pressure pulses were developed, like pain therapies for heel spur, tennis elbow and other orthopedic pain diseases [2, 3]. Most recent applications target the heart muscle [4] and seek for methods to target gene therapies by focused pressure pulses [5].

In clinical use Pressure Pulses are generated by electrohydraulic, electromagnetic or piezoelectric sources [6]. Due to the nonlinearity of the medium, the pressure pulses in the focus of a lithotripter usually have steep shock-like pressure fronts, which require measurements with high bandwidth.
2. Measurement of Pressure Pulses

2.1. History
The first measurements of pressure pulses were attempted with piezoelectric hydrophones, which were mainly designed for the measurement of shockwaves. The signals from these sensors allowed only estimations of single parameters like peak positive pressure or rise time; therefore reliable measurements of pressure, energy parameters, negative pulse portions and lateral and axial field distributions had errors >100% at first. In clinical papers of the early years, the usual statements about shockwave parameters were based on the kV setting of the electrical circuits of the lithotriters.

PVDF membrane hydrophones could measure the pressure pulses with high fidelity, but they are expensive and often damaged after only few pulses, mainly by cavitation. A significant step towards longer service life was the introduction of PVDF needle hydrophones [7], but some pulse parameters, in particular those of negative pressure portions and most energy parameters are still grossly underestimated due to refraction and resonance effects of the needle. In the 80s and 90s of the last century, most lithotriters on the market were characterized using these hydrophones [8]. In consequence a lot of biologic research data on effects and side effects used these data [9] and are therefore imprecise.

2.2. IEC 61846 measurement standard
In 1998, the IEC standard 61846 was published, defining the measurement parameters which describe both the temporal waveforms and the acoustic field of pressure pulse sources [10]. From this date the approval of newly designed lithotriters for clinical use was based on the measurement methods described in this standard. Although the standard originally was written for lithotriters, it is also used to describe pain therapy (ESWT) devices and their effects [11].

The standard 61846 allows the use of “focus” and “field” hydrophones. Focus hydrophones are specified to have a performance comparable to PVDF membrane hydrophones with 25µm membranes and small sensitive spots. As these hydrophones are very fragile, they may just be used to characterize the pressure waveforms in the focus, so they only have to survive a few pulses. More robust “Field hydrophones” have reduced specifications (e.g. the PVDF needle hydrophones). They may be used in the pressure pulse field regions outside the focus, where the signals usually have longer rise times and less high frequency components.

In IEC 61846 two sets of pressure pulse parameters are defined; the first set is derived from the pressure-time curves measured at the focus (e.g. Figures 4, 5): Positive and negative peak pressures $P_+$ and $P_-$, rise time $TR$ (10% to 90% of $P_+$), positive pulse duration $TD$ (50% of $P_+$ from rising edge to falling edge) and the Pulse Intensity Integral $PII(r, \theta) = \frac{1}{2\pi} \int_0^{\infty} p^2(r, \theta, t)\,dt$ which determines the energy flux density of the pressure pulse. The second set is field parameters: axial and lateral pressure distributions (FWHM = Full Width Half Maximum) and focus energy $E_R = \int_0^{\infty} PII(r, \theta)\,dS$. Correlations of the parameters to stone comminuting and biological effects are discussed in [6].

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1 Before 1998 the term of lithotripter waves was „shockwave“, as the electrohydraulic generated pulses in the focus usually had very short rise times in the range of a few nanoseconds. This term is still in widespread use. After the occurrence of other sources like electromagnetic and piezoelectric, it showed that pulses with slower rise times, which may occur at lower energy settings, also could disintegrate stones. In most pressure pulse sources, the rise time of the signals outside the focal area increases by some orders of magnitude [6].

2 $S$ is a circular area in the focus plane delimited by a diameter $R$, which, according to IEC 61846, shall be the diameter of the -6dB pressure amplitude isobar. As this value has not much significance for the evaluation of stone disintegration efficacy or biological (side) effects, other “effective” diameters like typical kidney stone sizes (12mm) or pressure isobars (e.g. 5 MPa, which is about the minimum pressure required for stone comminution), should be used [6], [7], [8], [9], [11], [15]
3. Optical Hydrophones – Physics and Technology
The physical principle of both the fiber optic hydrophone [12] and the light spot hydrophone [13] is based on the change of the refractive index of a fluid, when a passing pressure wave instantaneously changes the local density of the fluid, which is described for water by the Tait equation. This change of refractive index modulates the intensity of reflected light at a glass-fluid interface, which can be calculated with the Gladstone-Dale equation, relating the optical refractive index to the media density.

The fiber optic hydrophone was invented by Eisenmenger in 1988. A thin optic fiber transports an infrared laser beam. The bare end of the fiber is submerged in the fluid, usually water. The fraction of light, which is reflected at the fiber – fluid interface and transmitted back to the top end of the fiber, is detected by a photo diode via a directional fiber coupler. When the fluid density is changed by the passing pressure pulse, the reflected light intensity is modulated proportional to the acoustic pressure \( p(t) \) [12]. The hydrophone used in this study (FASO = FaserOptische SOnde, the same principle as Eisenmengers FOPH = FiberOPtic Hydrophone) uses a 812nm diode laser at 120 mW through a 125 µm optical fiber.

The light spot hydrophone (LSHD) uses a 90x60x30 mm glass block, which is submerged in the fluid at the lower side. The 785 nm, 35 mW diode laser beam is passed through a coupling fiber to a lens, which directs the beam from the air above through the glass block under an angle (ca. 15°). The beam is focused to 50 µm spot at the glass-fluid interface by the optic lens. A photo diode is placed analogous above the glass block to receive the laser light, which is reflected (\( R_{GW} = 0.16\% \)) at the glass-water interface. The intensity of the reflected laser light is modulated by the pressure pulse induced change of refractive index of the water beneath the glass block. As a portion of the pressure pulse also causes solid waves traveling through the glass block, only short pressure pulses can be measured unobstructed before the acoustic reflections from the upper (air) side of the glass interfere with impinging acoustic signals. For lithotripter and ESWT pressure pulses, 30 mm thickness of the glass block is chosen for undisturbed measurement of ca. 10µs pulse signals.

3.1. Calibration of the optical hydrophones
The in-situ calibration of both optical hydrophones does not need acoustic measurements. The calibration procedure of the LSHD only requires measuring the static reflected light intensity \( R_{GW|p=0} \) under two different interface conditions: Glass-air and glass-water. From these values the sensitivity can be calculated [13]. The typical sensitivity of the LSHD is -9.6 mV/MPa. If the glass surface is damaged by the pressure pulses, the glass block can be displaced horizontally by some centimetres by a precision screw without changing the positions of the laser and detector. Thus the position of the active spot in the pressure field is conserved and measurements can continue in an instant without the need to change the position of the hydrophone for re-calibration.

The FASO is calibrated by comparing the static reflected light intensities by submerging the fiber in isopropanol and in water. The typical sensitivity of the FASO is -0.27mV/MPa. If the fiber is damaged or broken, it can be cleaved to achieve a new surface, and then recalibrated using the two fluids. When steep pulses, impinging oblique in the fiber are measured, the reflected pressure adds a short time pressure peak, which is compensated by an edge diffraction wave, emerging at the periphery of the fiber (Figure 1). When this diffraction wave has travelled over the flat fiber surface to the center, it completely compensates the reflected pressure pulse signal. In order to display the correct pressure – time curve of the signal and to avoid over-estimation of the pressure pulse amplitude \( P^+ \), this additional spike needs to be removed, which requires an additional signal processing step.

3.2. Signal Processing
The signal processing serves two purposes: For the FASO, the removal of the additional spike can be achieved by deconvolution or by filtering the measured signal (Figure 1). As a reference signal for deconvolution, the hydrophone transfer function is needed.

For both FASO and LSHD, the photon noise of the laser source, which restricts the (non-averaged) use of the hydrophones to signals of \( P^+ > 1..2 \) MPa, can be smoothed by additional low pass filtering.
After filtering, additional linearization may be applied in order to correct the slight (<10% up to 120 MPa) non-linearity, which is caused by the non-linearity of the pressure induced density change of the fluid (Figure 2). As this non-linearity only leads to significant errors at pressures above ca. 50 MPa, this correction step may be omitted for smaller signals.

Figure 1: The leading edge of the fiberoptic hydrophone signal (red dots) shows a short peak, which is caused by the reflection of the impinging pressure pulse and is compensated after ca. 50 ns when the edge diffraction wave at the 125 µm fiber diameter has reached the center of the fiber tip. The LSHD signal (blue dots) doesn’t show this peak because the glass surface is 60*90 mm wide.

Figure 2: The optical refractive index \( R(p) \) is slightly non-linear (<10% in the usual therapeutic range up to \( P+ \) of 120 MPa), which should be corrected if pressures above ca. 50 MPa are measured (Data based on the LSHD glass parameters)

4. Measurements using Optical Hydrophones

4.1. Materials and Methods

The measurements were made in a prototype lithotripter source, which was originally built at the University of Stuttgart. The highly stable pressure pulse source is an electromagnetic type with a concave focusing membrane of 120 mm diameter and a focal distance of 200 mm (EMSE-01), giving a focus spot size of 11 mm (FWHM, at 13 kV energy setting). Additionally, it can be equipped with a Perspex lens, which reduces the focal distance to 100 mm and thus concentrates the acoustic pressure to a significantly smaller focus spot of 3.5 mm (FWHM). The system with additional lens is called EMSE-02. The lens allows an easy comparison of lesser and stronger focused pressure pulse fields at the same overall energy. Between our measurements, a damaged membrane of the EMSE had to be replaced; only measurements with the same membrane (marked “old” and “new”) are compared in this paper.

The pressure pulse source is mounted at the bottom of a tank, filled with degassed water (<2 mg/l \( O_2 \)) at 21+2°C temperature. The hydrophones can be moved by computer-controlled 3-axis gimbals with a resolution of 100 µm.

In order to determine the transfer functions of LSHD and FASO, the focus signals of a piezoelectric transducer (Panametrics: V307-SU, 5.0 MHz, diameter: 25 mm, focus distance: 95 mm, driven by a Panametrics Pulser-Receiver at 100V, 200V, 300V and 400V settings) were measured in the laboratories of the Fachbereich 1.62 Ultraschall, Physikalisch-Technische Bundesanstalt PTB,
Braunschweig with the PTB reference interferometric hydrophone [14]. From these measurements and measurements of the FASO at the same focus distance, the transfer function of FASO was calculated.

**Figure 3:** Deconvolved 5 MHz Panametrics (300 Volt) signal of FASO vs. PTB reference interferometer signal. At these low pressures, even averaged (N=64) FASO signals are noisy due to the laser photon noise. Parameters:

|               | Reference | FASO |
|---------------|-----------|------|
| \( P^+ (1^{\text{st}}/2^{\text{nd}}) \) | 2,1/3,06MPa | 2,4/2,75MPa |
| \( P^- \)     | -1,27 MPa  | (peak:-2,3)/-1,85MPa |
| \( T_R (1^{\text{st}}/2^{\text{nd}}) \) | 7 / 10 ns   | 7 / 7 ns     |
| \( \text{PII (64,7\,\mu s)} \) | 0,309\,\mu J/mm\(^2\) | 0,307\,\mu J/mm\(^2\) |

4.2. Results

The results of the FASO calibration with the Panametrics 5 MHz transducer at 3,06 MPa are demonstrated in Figure 3. Figures 4 compares the FASO vs. LSHD focal pressure pulse signals of EMSE-01 at 13 kV setting. The EMSE-01 vs. EMSE-02 13 kV focus and field parameters (Figure 5) were measured with LSHD. IEC 61846 Pressure pulse parameters are given beside the figures.

**Figure 4:** Comparison of LSHD and FASO measurements in the focal maximum of EMSE-01 (13 kV, old membrane). While the FASO signal was deconvolved; the LSHD signal was not filtered.

|               | FASO     | LSHD      |
|---------------|----------|-----------|
| \( P^+ \)     | 29,8 MPa | 29,6 MPa  |
| \( P^- \)     | -5,3 MPa | -5,3±1MPa |
| \( T_R \)     | 20 ns    | 20 ns     |
| \( T_D \)     | 760 ns   | 780±20 ns |
| \( \text{PII}^+ \) | 0,40mJ/mm\(^2\) | 0,41mJ/mm\(^2\) |
| \( \text{PII}_{\text{ges}} \) | 0,50mJ/mm\(^2\) | 0,53 mJ/mm\(^2\) |

**Figure 5:** LSHD measurements of the focal pressure pulses of EMSE-01 and EMSE-02 (both at 13 kV; new membrane). Pressure pulse parameters according to IEC 61846:

|               | EMSE-01   | EMSE-02   |
|---------------|-----------|-----------|
| \( P^+ \)     | 36,4 MPa  | 76,1 MPa  |
| \( P^- \)     | -10,3 MPa | -15,0 MPa |
| \( T_R \)     | 7 ns      | 220 ns    |
| \( T_D \)     | 850 ns    | 450 ns    |
| \( \text{PII}_{\text{ges}} \) | 0,43mJ/mm\(^2\) | 1,04mJ/mm\(^2\) |
5. Discussion

With the optical hydrophones LSHD and FASO, high fidelity measurements of lesser and stronger focused pressure pulse sources could be made. Processed pressure – time signals of both hydrophones at the same position in the pressure pulse fields are in very good agreement for pressures > 2 MPa.

Both hydrophones have the following advantageous properties: (+) good signal reproduction; (+) fast repair; (+) no acoustic calibration necessary; (+) high bandwidth; (+) long service life with low-cost spare parts (+); can be used as “Focus” and “Field” hydrophones according to IEC 61846.

The active part of the fiberoptic hydrophone (FOPH, FASO) additionally is (+) very small and flexible, but it (-) easily breaks due to cavitation and thus needs frequent cleaving and readjustment of the fiber, which may extend the measurement time at high energy settings and less-degassed water.

Disadvantages of the FOPH are its (-) large sensor head and the need for (-) upright positioning, as laser and photodiode need to be in air. The glass block LSHD is (+) robust and cavitation resistant, and in case of cracks in the glass it (+) can be repaired in an instant by shifting the position of the glass block without loss of the active spot position in the pressure pulse field, thus enabling fast and reliable measurements of pressure pulse fields.

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