Characterization of intense pressure pulse through cylindrical hole

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1. Introduction

Intense compressive pressure pulses with short duration, which are known as shockwave, are used for widely used for noninvasive treatment such as calculi destruction in human body [1]. On the other hand, Ohl and co-workers have been reported the cell detachment and molecular uptake into cells by a single focused shock wave generated using an extracorporeal shock wave lithotripter [2]. Hasebe and co-workers also have reported the molecular uptake into the human cells seeded on the culture dish bottom without focusing single underwater shockwave [3]. A single pressure pulse is sufficient to permeabilize the stratum corneum (SC) as well as the cell membrane. Therefore, this becomes one of promising candidates for transdermal drug delivery [4].

To realize the targeted transdermal drug delivery, it is necessary to irradiate a specific area range with a pressure pulse while keeping the sufficient intensity. Recently, we have reported the effect of a cylindrical hole on the propagation of the single underwater shock wave generated by the spark discharge [5]. The pressure pulse propagated through a cylindrical through-hole involved large pressure in comparison with that propagated in free space. However, the propagation characteristics of the pressure pulse through a cylindrical hole with several diameters are not investigated in detail. In this study, we numerically and experimentally investigated the effect of the cylindrical through-hole with different diameters on the propagation of single pressure pulse generated by underwater spark discharge.

2. Preparation

2.1. Pressure pulse generation and electrical measurement

A high voltage is applied between two needle electrodes installed in water using an impulse voltage generator to induce a spark discharge and generate an underwater shockwave. This generator includes a charging circuit and a gap switch (GS). The boosted and rectified AC voltage is charged in five parallel-connected capacitors (each capacitance of 1,700 pF). When a GS turns on, the charged voltage in the capacitor is applied to the Tungsten needle electrode (tip radius is 25 μm) installed into a groove of Teflon block [3]. In this experiment, the GS interval and needle tip distance

were fixed at 3 mm and 2 mm, respectively. The applied voltage and the discharge current were measured using a high-voltage probe (Nissin Pulse Electronics, EP-50K) and a current transformer (Peason Electronics, 110). These waveforms were measured using a digital oscilloscope (Iwatsu, DS-5654A). Table 1 shows the summary of the charge and discharge parameters used in the pressure pulse generation.

2.2. Preparation of cylindrical through-hole and pressure measurement

Figure 1 shows the illustration of a cylindrical hole formed in the solid plate and of Teflon block with the discharge needles installed in a groove. The width and depth of a groove are respective 4 mm. A polycarbonate (PC) was used as plate material because of faster sound speed than water at the same temperature, excellent electrical insulation and shock resistance. The diameter D of the cylindrical through-hole was varied from 0 to 5 mm. The PC plate thickness, which corresponds to the hole length, was fixed at 5 mm. This length is ten times larger than that the pulse width (multiply velocity by pulse duration). A through-hole center is located at the middle between the discharge needle tips. The PC plate with a through-hole was fixed on the Teflon block with discharge electrodes. In this case, the entrance of a through-hole was located above 2 mm from the electrode. They were immersed in acrylic tank (100 $\times$ 200 $\times$ 100 mm) containing pure water. A part of the pressure pulse generated by spark discharge propagates through the water-filled cylindrical hole. The tip of a hydrophone sensor (Muller Platte Needle Probe, rise time 50 ns, sensitive diameter <0.5 mm) was placed at the position of 1 mm away from the exit of a through-hole. In this experiment, the distance from the needle electrode to the tip of the hydrophone sensor was fixed at 8 mm.

2.3. Numerical simulation method

In order to comprehend the pressure pulse propagation in a through-hole with different diameters, the numerical analysis was performed by finite-difference time-domain (FDTD) method using a cross-sectional two-dimensional (2D) model with a pressure source located on the central axis [6–8]. It is known that three-dimensional analysis is necessary. We however consider that this 2D model is useful to understand the pressure pulse propagation in the through-hole, because this through-hole is axially symmetric. The parameters using

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Table 1 Parameters of underwater spark discharge.

Parameters	average $\pm$ S.D.
Charged voltage	10.6 ± 0.4 kV
Discharge current	326 ± 21 A
Discharge power	1.78 ± 0.11 MW
Discharge Energy	0.46 ± 0.03 J

Fig. 1 Top and cross-sectional views of a cylindrical through-hole formed in the PC plate which was placed upward the discharge needles installed in a groove of the Teflon block. They are immersed in pure water. Simulation space (10 mm $\times$ 10 mm) is shown as an area surrounded by red-dashed line.

Table 2 Parameters using 2D-FDTD simulation.

Parameters	Values
Number of division	400 $\times$ 400
Increments in space, $\Delta x = \Delta y$	25 μ m
Increment in time, Δt	4.27 ns
Courant number	0.256 in water
Input waveform	Gaussian
Formula of input temporal waveform	$200e^{-(\frac{t}{t_d}-5)^2}$
Width of input waveform, t_d	0.245 μ s
Boundary condition	Higdon's 2nd-order absorption boundary
Nonlinear parameter of water	3.5
Density and sound velocity of water	1,000 kg/m ³ and 1,500 m/s
Density and sound velocity of PC	1,198 kg/m ³ and 2,280 m/s
Density and sound velocity of Teflon	2,180 kg/m ³ and 1,380 m/s

2D-FDTD was shown in Table 2. To calculate the propagation in the space (10 mm $\times$ 10 mm, Fig. 1) including a PC plate with a through-hole and Teflon block, the increments in

space $\Delta x = \Delta y = 25 \mu$ m and in time $\Delta t = 4.27$ ns were chosen. A Gaussian pulse with amplitude of 200 MPa was applied to a point source as input signal. The propagation loss was neglect. Higdon's absorbing boundary condition was applied to the outer boundary of the analytical space [9]. The density and longitudinal velocity values of water (1,000 kg/m³, 1,500 m/s), PC (1,198 kg/m³, 2,280 m/s), and Teflon (2,180 kg/m³, 1,380 m/s) were used in this calculation. In order to discuss the first arrival wave in a liquid medium, transverse waves in solid media were not calculated.

3. Results and discussion

3.1. Pressure waveforms

Figure 2 shows the 2D-FDTD simulation and experimental results of the temporal pressure waveforms after passing through a hole with various diameters. The pressure waveforms without PC plate (in free space) were also shown in this figure due to comparison. In the experimental results, the time at the maximum discharge power was set to 0 seconds. The positive peak pressure increased with increasing hole

Fig. 2 2D-FDTD simulation and experimental results of pressure waveforms after passing through a hole with various diameters. The waveforms in free space also show due to comparison. Asterisk (*) indicates the reflected pulse from the boundary between water and PC plate inside the hole.

Fig. 3 Variations of the positive peak pressure, when the diameter of the through-hole was varied from 0 to 5 mm. The results in free space were also shown due to comparison.

diameter. The negative pressure component was also observed after the positive pressure pulse, however, it was smaller than that of the simulation results. The reflected pulses from the boundary between water and PC plate of the hole inside were appeared following the first positive pulse, when the diameter was larger than 3 mm in this simulation. The increase in pressure is occurred due to the overlap between the direct pulse and the reflected pulses propagating in the hole inside.

3.2. Pressure variable after propagating through-hole

Figure 3 shows the variation of the positive peak pressure, when the diameter of the through-hole was varied from 0 to 5 mm. The results in free space were also shown in this figure. Comparing the simulation with the experimental results, the diameters at which the maximum peak pressure was obtained were different. The positive peak pressure after propagating through-hole became maximum at diameter of 2 mm in simulation, whereas, of 3 mm in experiment. This difference indicates that the pressure source of the experimental model is not necessarily located only on the central axis. We suppose the formation of a linear pressure source along the discharge path. However, tendency of the peak pressure variation was similar. In this experimental results, the maximum value of the positive peak pressure became about 1.5 times large (32 MPa), as compared with that (20 MPa) in free space.

3.3. Pressure distribution on PC plate with cylindrical through-hole

Figures 4(a) and 4(b) show the pressure distribution along normal and parallel directions to the groove, respectively. A through-hole with the diameter of 4 mm was used in this measurement. The positive pressure values were measured by moving the hydrophone sensor along the horizontal direction from the central axis of the through-hole. Although the largest pressure value was obtained on the central axis, it was approximately 20 MPa in free space. On the other hand, the pressure values larger than 20 MPa were obtained in the through-hole range from the center to about 1.0 mm, and decreased sharply at the position of 2 mm from the center. It was displayed that a maximum intensity over 30 MPa was obtained at the hole center in this experiment (Fig. 4).

Fig. 4 Pressure distributions along (a) normal (x -axis) and (b) parallel (y -axis) directions to the groove. A through-hole with the diameter of 4 mm was used in this measurement. The positive pressure values were measured by moving the hydrophone sensor along the horizontal direction from the central axis of the through-hole.

In transdermal drug delivery with a single photomechanical pressure, a peak pressure pulse exceeding 50 MPa has been used and 35 MPa is reported as the permeation pressure threshold for SC [4,10–13]. Proposed method is useful for reducing the applied energy used to generate pressure pulses and for obtaining high-intensity pressure pulses.

4. Conclusion

We have found an experimental condition which an intense pressure is formed by propagating single pulse through a cylindrical hole. According to our study, the ratio between the length and diameter of the through hole was 0.6 to 0.8 as suitable condition. When a pressure pulse was propagated through a 4 mm diameter cylindrical with the length of 5 mm, a positive peak pressure value about 1.5 times larger than that in free space propagation was obtained on the central axis of the through-hole.

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