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A cylindrical waveguide with different diameters for extracting high-intensity pressure pulse of underwater spark-induced shock wave and for suppressing the impact of cavitation

水中火花誘起衝撃波の高強度圧力パルス抽出とキャビテーションの影響を抑制するための直径の異なる円筒導波路

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1. Introduction

High pressure pulse generated in water (underwater shockwave) is used not only for calculi destruction in human body[1)], but also for introduction of foreign substances into human cells [2)]. We have irradiated without converging the single underwater shock wave to the human cells seeded on the bottom of the culture vessel in application to the foreign substance introduction[3)]. In this experiment, shock waves were induced by underwater spark discharge directly under the culture vessel.

In underwater spark discharge, the generation and expansion of cavitation bubbles occur simultaneously with the generation of shock waves. It is well known that cavitation bubbles around solid walls are deformed or broken by the impact pressure of micro jets generated by their collapse[4-6)]. This fact is serious when the culture vessel in which the cells are seeded is irradiated with a underwater spark-discharge-induced shock wave. This problem can be avoided by separating the sufficient distance between culture vessel and shock wave source, however, the intensity of the shock wave is reduced in inverse proportion to distance in free space.

In the previous report, Kobayashi et al. have reported that underwater spark discharge-induced shock waves propagated through waveguide can be extracted with high intensity[7)]. In this experiment, a 4-mm-diameter circular hole drilled in a 5-mm-thick polycarbonate (PC) plate was used as a waveguide and its waveguide was placed just 2 mm above a discharge electrode pair. However, even in this experimental configuration, the culture vessel installed at the exit end of the waveguide was damaged.

It is assumed that the influence of cavitation bubble expansion acts far away in a waveguide filled with incompressible fluid. Althogh a method of using waveguides with different diameters is conceived as solution, there is no report confirming its effect. In this study, we experimentally confirm that high-intensity pressure waves can be extracted by suppressing the influence of cavitation using cylindrical waveguides with different diameters.

2. Experimental Procedure

Figure 1 shows the relationship between the cylindrical waveguide with different diameter and the acoustic source in the side and top view. The central location of the discharge electrode pair corresponds to that of the acoustic source, and it is placed 2 mm below on the central axis of the cylindrical waveguide. The waveguide diameter D_1 and D_2 are fixed at 4 mm and 14 mm, respectively. The length of upper cylindrical waveguide with diameter of D_2 is changed at the range from 0 to 8 mm. The PC plate thickness h is fixed at 10 mm. This PC plate with double cylindrical waveguides is immersed in an acrylic tank (100 x 200 x 100 mm) containing pure water. The tip of a hydrophone sensor (Muller Platte Needle Probe, rise time 50 ns, sensitive diam. <0.5 mm) was installed at the position of 1 mm away from the end of the cylindrical waveguide.

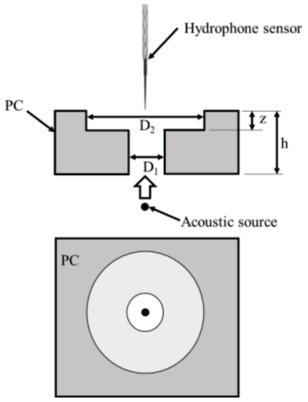

Fig. 1 Schematic illustrations of a cylindrical waveguide with different diameter shown in side view and in top view. The location of an acoustic source and a hydrophone sensor is indicated in the upper figure.

A impulse voltage is applied to a needle electrode pair installed in water in order to induce a spark discharge and generate an underwater shock wave. This impulse generator includes a charging circuit and a gap switch (GS). When a GS turns on, the charged voltage in the capacitor is applied to the needle electrode attached to the shock wave irradiation device[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 (Nisshin Pulse Electronics, EP-50K) and a current transformer (Peason Electronics, 110). These temporal waveforms were measured simultaneously with the hydrophone sensor signal using a digital oscilloscope (Iwatsu, DS-5654A).

3. Results and discussion

Figure 2 shows typical pressure waveforms after propagating with cylindrical waveguide (z=6 mm) and after without waveguide. These waveforms were measured on the central axis of the cylindrical waveguide. From these results, the waveform shape with the cylindrical waveguide almost unchanged in comparison with that without waveguide. The maximum pressure value, however, increased in the case of using the cylindrical waveguide. The pressure wave propagating through the cylindrical waveguide showed large positive pressure with steeply rising and small negative pressure with slow changing after positive peak pressure. The average pressure, which was obtained by three measurements, was 9.2 MPa in the case without the cylindrical waveguide, whereas it was 21 MPa in the case with cylindrical waveguide (z=6 mm). When the length z value of the cylindrical waveguide with a diameter of 14 mm was varied between from 0 to 8 mm, the maximum pressure value increased with increasing z and became the maximum at z = 6 mm, whereas it decreased at z=8 mm. The discharge voltage and discharge energy in this experiment were 10.1 ± 0.5 kV and 0.35 ± 0.4 J, respectively. In the numerical simulation, the overlapping of the constructive wave by the reflected wave and the direct wave was confirmed.

Finally, we irradiated a high pressure pulse with maximum pressure of 20 MPa and more using cylindrical waveguides (z=6 mm) to HeLa cells (derived from human cervical cancer, 10^4 cells) seeded in a glass-based dish (IWAKI, φ12 mm). The microscopic observation of the cells after irradiating a high intensity pulse was performed in the range of 3.29 mm×3.10 mm in the bottom of the glass base dish. As results obtained, the cells were detached only in the central area of the glass-based dish, and the detached regions were concentrated in the range of 0.62 mm×0.47 mm. From the pressure distribution measurement at the end of the cylindrical waveguide (z=6 mm), the region where the maximum pressure exceeds 20 MPa was limited to a radius of 1 mm or less.

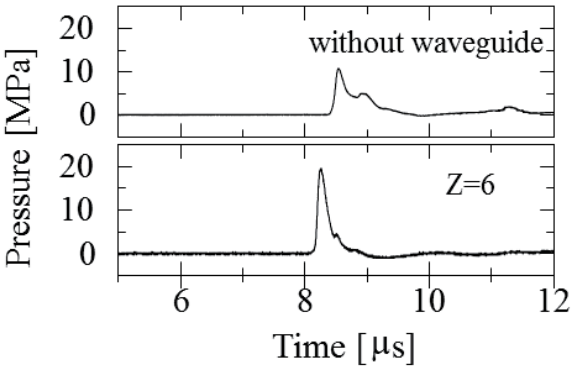

Fig. 2 Typical pressure waveforms after propagating with cylindrical waveguide (z=6 mm) and after without waveguide (upper figure).

4. Conclusion

A cylindrical waveguide with different diameters is useful for irradiating a high-intensity pressure of underwater spark-induced shock wave into the cultured cells without breaking the culture vessel.

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