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Acoustic field simulation for bending thin catheter considering reflection in enclosed space

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1. Introduction

Because we have already developed the methods to control the behavior of microbubbles by making use of acoustic radiation force, we have applied the method to bend a thin catheter [1-4]. Using a 2D array transducer (hereinafter, 2D array), which can produce an arbitrary shape of acoustic field and bring about dynamic changes in an acoustic field, we succeeded to bend it in the direction perpendicular to ultrasound propagation in water [2,3] or viscous liquids [4]. In addition, considering the actual application, we proposed a method to detach the catheter from the vessel wall by applying vibration to the problem of adhesion between the catheter and the vessel wall [5]. However, we have not been able to theoretically predict or evaluate how the catheter would behave in a sound field with a situation including a reflection caused by bones. Considering an application to cerebrovascular catheterization operation, because the sound source position is limited, a precise simulation method, which realizes acoustic field reproduction with multiple reflections in the skull as an enclosed space, is mandatory. Therefore, we developed a method to simulate spatial distribution of sound intensity, which related to the direction and magnitude of the acoustic radiation force, and compared the results with the experimental trajectory of the catheter using a reflective plate.

2. Theory

According to the conventional Langevin theory, acoustic radiation force F_p applied on a cylinder, representing the shape of a thin catheter, which axis was set in the perpendicular direction of ultrasound propagation, is expressed as eq. (1) with acoustic radiation function Y_p:

$$F_p = ES_pY_p, \qquad (1)$$

where E and S_p indicate acoustic energy density and the effective area on the cylinder, respectively. Also, according to the preceding research [6], acoustic radiation force function Y_p can be expressed as:

$$Y_p = -\frac{2}{kr_o}\sum_{n=0}^{\infty}[\alpha_n + \alpha_{n+1} + 2(\alpha_n\alpha_{n+1} + \beta_n\beta_{n+1})], \qquad (2)$$

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where k is the wavenumber, r_o is the outer radius of the cylinder, and α and β are the real and imaginary parts of the scattering coefficient calculated from sound velocity and density of the cylinder material, surrounding medium and inner medium. In this research, since we calculated the distribution of acoustic energy density E by dividing that of sound intensity by sound velocity of the medium, the direction and magnitude of the acoustic radiation force F_p are calculated. The average sound intensity is temporary calculated and obtained as two-dimensional vector in the following simulations.

3. Method

The method of calculating the sound field was based on the mathematical model of k-Wave [7]. The mechanical parameters of the 2D array, such as the delay time setting, are the same as those used in our own equipment. The 2D array has 128 elements of a central frequency of 3MHz. **Figure 1** shows simulation space including the 2D array and an elliptical reflector. Also, we prepared the experimental setup with the same arrangement. We discuss the following results in *x-z* plane.

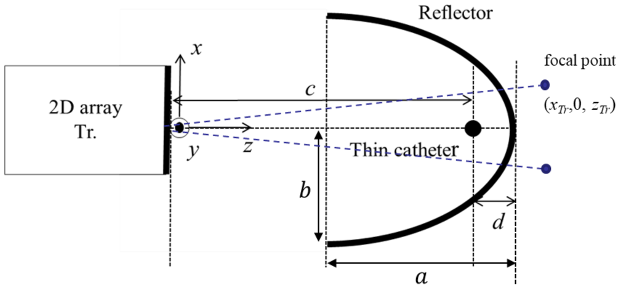

Fig. 1 Simulation space including 2D array and reflector.

The material of the reflector was aluminum, which has a sound velocity of 5200 m/s and a density of 2700 kg/m^3. The reflection coefficient between aluminum and the medium (water) is 0.81. Because the elliptical shape has two foci, the sum of the distances from two foci to any boundary point in a plane is constant. Therefore, it is suitable to verify ultrasound dispersion and focusing. The element surface of 2D array and the tip of the catheter were located at (0, 0) and (0, 80), respectively, both of which are foci of the ellipse shape. As well as our preceding research [3,4,5], we adopted tempo-spatial division emission to produce burst waves, where the

PRT was set at 10 ms and 5 μs in the experiment and the simulation, respectively, to reduce calculation cost in the simulation. **Table 1** shows the specific distance and ultrasound parameters shown in Fig. 1.

Table 1 Specific distance and ultrasound parameters

Sound pressure [kPa-pp]	600
Frequency [MHz]	3
PRT[μs]	5
duty ratio[%]	60
Focal position z_{Tr}[mm]	102
Focal position x_{Tr}[mm]	5,-5
semi-major axis a [mm]	51
semi-minor axis b [mm]	31
x-axis distance of catheter to Tr. c [mm]	80.02
y-axis distance of catheter to Reflector d [mm]	10.14

4. Results

Figure 2 shows the spatial distribution of mean sound intensity when single focal point was formed at (5, 102) in the simulation, where magnitude of the sound intensity was corresponded to the color bar. Also, the trajectory of the tip of the catheter obtained from the experiment was superimposed on Fig. 2 as blue circles, where the sampling time interval was 24 ms. From the initial position, the catheter was bent in the direction of (-1.16, 77.8), which is corresponded to the vector of mean sound intensity near the initial position.

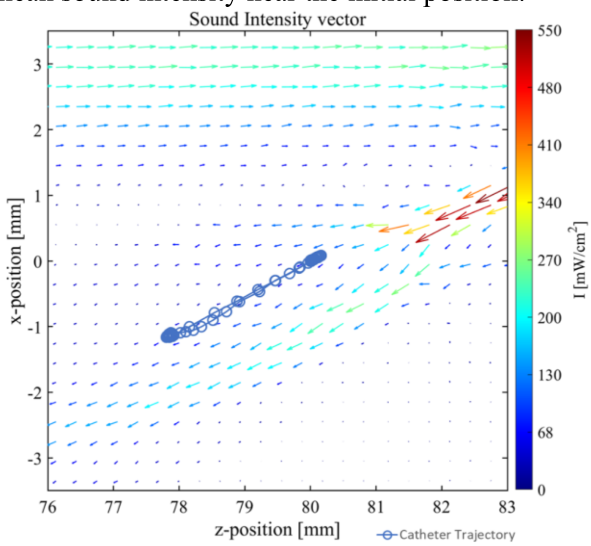

Fig. 2 Distribution of sound intensity with the actual trajectory of the catheter with focal point of (x,z) = (5, 102).

Figure 3 shows similar combination when two foci were formed simultaneously at (5, 102) and (-5, 102). There are nine trajectories to indicate experimental results, which indicate nine patterns of the initial position of the tip of the catheter along x-axis with the interval of 0.5 mm. It is confirmed that the displacement of the catheter was maximum when the tip was located at the elliptical focus, and decreased away from the focus. When the initial position of the tip was (-1.5, 80), both of sound intensity and the trajectory showed the minimum, which results were corresponded, since the travelling wave and the reflected wave were cancelled.

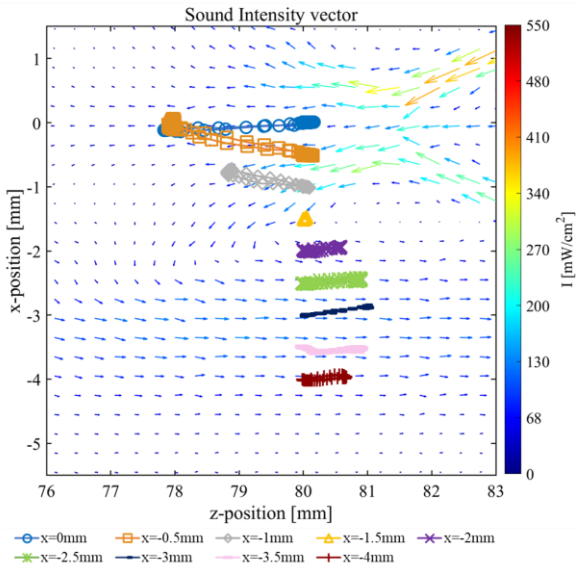

Fig. 3 Distribution of sound intensity with the actual trajectory of the catheter with focal point of (x,z) = (5, 102) and (-5, 102).

Through the comparison between the simulation and the experimental results, we confirmed fair correspondence between the spatial distribution of mean sound intensity and the trajectory of the tip of the catheter. Because the displacement of the catheter depends on the length of the catheter, prediction of the direction of the tip is useful not only for the fundamental experiment to verify the behavior of the catheter but also for future in vivo applications.

5. Conclusion

We have simulated the distribution of acoustic field considering reflections in an enclosed space and verified through actual experiments with the same conditions. Comparison between them showed a fair correspondence in the direction and magnitude of the catheter displacement. We are going to investigate the simulation with more complex situation toward cerebrovascular catheterization operation.

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