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Optimization of the thin waveguide for double-parabolic-reflectors ultrasonic transducers (DPLUS) for minimally invasive thermal treatments

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1. Introduction

Minimally invasive thermal treatments (MIT) have received wide attention since the 1990s. It requires the insertion of a thin applicator (usually <10 mm OD (outer diameter)) to the tumor for delivering the thermal energy. MIT can be used for hyperthermia and thermal ablation. For hyperthermia, the tumor is heated up to ~42.5-45 °C for 30-60 mins; for thermal ablation, the tumor is heated to over 52-56 °C and less than 1 min for inducing the coagulative necrosis. By transmitting ultrasound through a thin acoustic waveguide (AW) for MIT is a recently developed method, which has recevied certain attenuation. However, to the best of our knowledge, no AW in the literature demonstrated any tissue ablation experiments due to the low acoustic output $\ll 1\ \mathrm{kW/cm^2}$.

In this paper, we try advancing the AW towards thermal ablation applications by introducing double parabolic reflectors wave-guided ultrasonic transducer (DPLUS) and optimizing the design of the DPLUS thin waveguide.

2. Methods and Results

Double parabolic reflectors wave-guided ultrasonic transducer (DPLUS) which can realize high-intensity acoustic output from the thin waveguide is shown in Fig. 1. The 1st parabolic reflector is designed for focusing the incident ultrasound generated by the PZT, and the 2nd reflector is for generating the plane wavefront ultrasound. Such plane wavefront ultrasound is found suitable for exciting the propagation modes in the thin waveguide. In the current design, the focal length of the 1st and 2nd parabolic reflectors is 10 mm and 0.5 mm, respectively. Two parabolic reflectors have the same focal point. By two parabolic reflections, the vibration amplitude of the emitted wave by PZT is improved to ~10 times near 1-2 MHz [1]. The DPLUS double-parabolic-reflectors waveguide is shown in Fig. 1(b). It was made of duralumin A2017 because of its low loss, high strength, and good machinability. An assembled prototype is shown in Fig. 1(c). In this study, the fused quartz fiber from Microsonic Co., Ltd. (Tokyo, Japan) was used as the DPLUS thin waveguide, which has the diameter of 1.2 mm. Two prototypes were fabricated: one with a PZT (PZT 18K, NGK Spark Plug Co., Ltd., Nagoya, Japan) thickness of 2 mm working at 1.0282 MHz and the other with a PZT thickness of 0.98 mm working at 2.2579 MHz.

Here, a 40 mm long thin waveguide was used. Longer length such as 1 m is indeed required for practical applications, however, this study focuses on the optimization of the working frequency and the diameter of the thin waveguide which does not necessarily require a long thin waveguide.

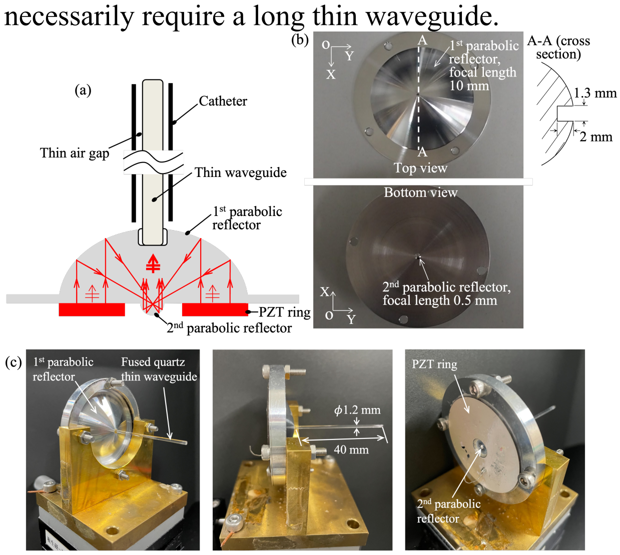

Fig. 1. DPLUS. (a) Illustration of DPLUS. (b) A fabricated DPLUS double-parabolic-reflectors waveguide. (c) An assembled DPLUS prototype.

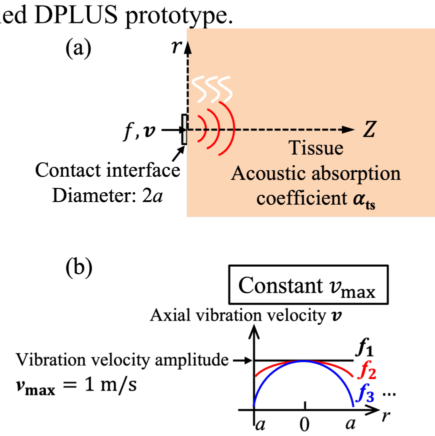

Fig. 2. Theoretical model. (a) A simplified model of DPLUS and tissue. (b) The axial vibration velocity model at the contact interface.

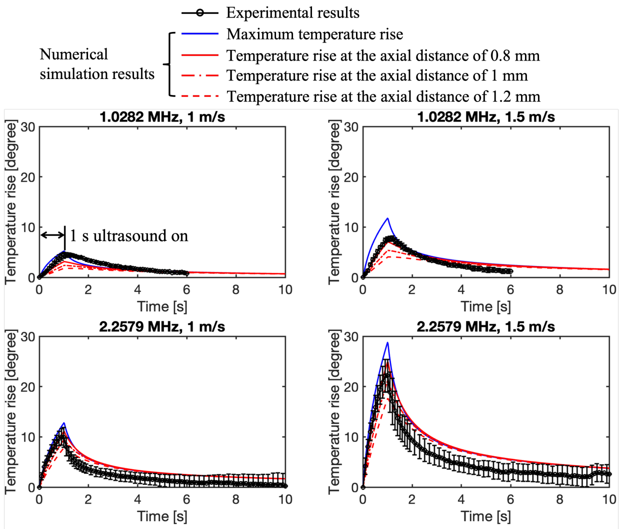

Fig. 3. Temperature rise curves.

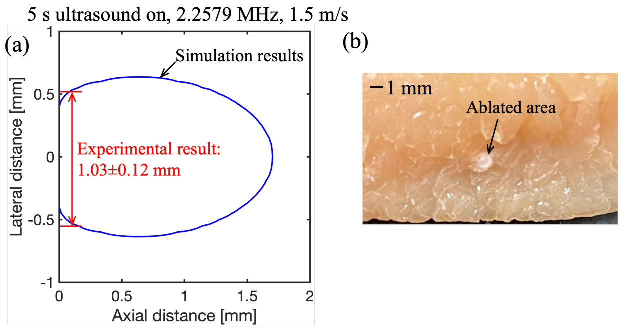

Fig. 4. Thermal ablation. (a) Size of the ablated tissue. (b) A photograph showing the ablated tissue.

Figure 2 shows a simplified model of DPLUS for thermal treatments. Only the contact interface between the thin waveguide and the tissue is modeled as shown in Fig. 2(a). The thin waveguide has a radius of a, which equals to that of the contact interface. There are only traveling waves in the tissue. The axial vibration velocity at the contact interface between the thin waveguide tip and tissue from $r = 0$ to $r = a$ is denoted as v, which has certain vibration shapes according to the propagation modes in the thin waveguide. The maximum value of the axial vibration velocity v along the radial direction (from $r = 0$ to $r = a$) is denoted as vibration velocity amplitude $v_{\max}$, which is modeled as a constant as illustrated in Fig. 2(b). This constant was set as 1 m/s. By varying the ultrasonic frequency f of the propagating wave, the axial vibration velocity v changes based on the Pochhammer-Chree wave theory, which further changes other fields in the tissue including the acoustic intensity field I, the ultrasound power deposition field q, and the temperature field T. The relation between the thin waveguide radius a, the ultrasonic frequency f and the temperature field T can be established from the modeling.

Modeling results showed that optimal a/Λ=0.2392 (thin waveguide radius/wavelength) can be found, and the optimal thin waveguide radius a depends on the excitable vibration amplitude in the thin waveguide. To verify the modeling results, thin waveguide radius a of 0.6 mm was selected in the experiments, and then we need to verify that the optimal frequency is at 2.2 MHz.

Temperature rise curves under 1-s ultrasound exposure and $v_{\max}$ of 1 and 1.5 m/s were summarized in Fig. 3. Temperature rises were measured by a K-type thin film thermocouple (GMT-TC-SB7.5, GEOMATEC Co., Ltd., Yokohama, Japan). The temperature baseline is 20 °C. For the numerical results in Fig. 3, the maximum temperature rise in the tissue is shown by the blue curves, which occurs at the lateral distance of 0 mm and axial distance of 0.25 mm and 0.47 mm for 1.0282 MHz and 2.2579 MHz, respectively. To consider the possible temperature changes caused by the positioning error of the thermocouple, the temperature curves at the lateral distance of 0 mm and axial distance of 0.8 mm, 1 mm, and 1.2 mm were also shown. The experimental results have good agreements with the numerical simulation results, which indicates that the presented modeling methods are effective.

The blue curve in Fig. 4(a) shows the ablated tissue from the simulation based on the thermal dose calculation [2], under the excitation of 2.2579 MHz and 5 s and vibration velocity amplitude $v_{\max}$ of 1.5 m/s. The size is ~1.2 mm wide and ~1.7 mm in depth. The maximum simulated temperature rise in the tissue is ~60 °C (with the baseline temperature 20 °C). Fig. 4(b) shows the ablated tissue in the experiment, where a color change can be observed. Trials at three locations showed an average ablation width of ~1.03 mm, with the standard deviation of 0.12 mm. The size is similar to the simulation results.

3. Conclusion

The results presented in this paper proved that the DPLUS system enables to advance the existing AW towards thermal ablation applications.

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