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Fundamental Study of Various Taste Solutions by Ultrasonics

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In this paper, the possibility of taste sensing is considered for five basic taste solutions and marketed beverages by making use of their ultrasonic characteristics. First, sound velocities are discussed in basic taste solutions and beverages at frequencies of approximately 2 MHz. Second, a novel layered medium is proposed for acoustic impedance matching devices with metals, and experimental results are shown for ultrasonic pulse transmission. Finally, the feasibility of taste sensing using the ultrasonic characteristics of a layered medium is discussed.

1. Introduction

As elucidations about the chemical senses of human beings are advanced, biosensors and chemical sensors are being developed which imitate the structure of chemical senses. Further, "taste sensors" and "odor sensors" are put to practical use with various lipid membranes.(1,2) Taste sensors have been studied using surface plasmon resonance and surface photo voltages.(3,4) In particular, the application of surface acoustic devices as ultrasonic devices to the sensors is reported not only for discrete tastes but also for solutions of taste substances.(5) Ultrasonic sound propagates with different characteristics in various materials. Its propagation characteristics reflect structures and properties of the materials. Therefore, research on the propagation of ultrasonic sound is very important for evaluating physical properties of liquids or solutions. There is the possibility that ultrasonic sound may become an effective method of taste sensing.

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Two kinds of experiments are reported in this paper. As experiment I, ultrasonic pulses are directed incident to some taste solutions, and we examine the possibility of taste sensing from changes in velocities of the ultrasonic pulses. The taste and deliciousness of food which humans sense are composed of many factors: sweetness, acidity, saltiness, bitterness, and umami, which are the five basic tastes. In previous studies, the five basic tastes were detected by the electric response and optical response of lipid membranes. We also used solutions of these five tastes as standards. Moreover, interactions of tastes which strengthen each other and weaken each other are known in several taste mixtures. A counterbalance effect and a contrast effect were examined as interactions of tastes in our experiments. Sound velocities were also measured by sound propagation in marketed beverages.

An acoustic impedance matching device is necessary to improve the transmission of the ultrasonic sound to water or taste solutions. For this purpose, a novel layered medium was fabricated. Ultrasonic pulses were directed incident to water by placing the layered medium between the pulser and water in experiment II.

2. Experiment I

2.1 *Materials and methods*

We used five taste solutions which contained chemicals typical of each basic taste, i.e., HCl for sourness; NaCl for saltiness; quinine for bitterness; sucrose for sweetness; Na-glutamate for umami. Concentrations of those solutions ranged from 0.1 to 1000 mM. Beverages were made by Kirin Beverage Company: "straight tea in the afternoon," "tea with lemon," "earl grey," "milk tea," "orange juice" and "tomato juice." The temperature of the solutions was set to 22±1°C during experiments. The outline of the measurement system is as follows: An electric impulse is produced by a pulser (made by PANAMETRICS Company, Model 500PR) and is transformed into a ultrasonic pulse by a transducer (made by PANAMETRICS Company) at frequencies around 2.25 MHz. The ultrasonic pulse is transmitted into a solution from the transducer. The pulse propagates in the solution and is reflected at the end of a cell filled with the solution. The reflected ultrasonic pulse is transformed to an electric signal by the same transducer. The signal is observed with a digital oscilloscope (made by SONY Tektronix Company, model TDS3012) and analyzed by a computer. Sound velocities are calculated from propagated distances divided by the time intervals between the ultrasonic pulses received.

2.2 *Results and discussion*

Concentrations of the five basic taste solutions were set at the unique value of 100 mM by measuring the velocity of sound passing through them. Figure 1 shows sound velocities in the five basic taste solutions and in water which is not mixed with any taste substances. The water was passed through an ion-exchange membrane after distillation. We observed definite differences between sound velocities in the sweet solution and those in the salty solution. The sweet solution is nonelectrolytic. In contrast, the salty solution is strongly electrolytic. We conclude that the difference between the sound velocities is caused by the electrolytic characteristics of the two solutions. The sweet solution and bitter solution

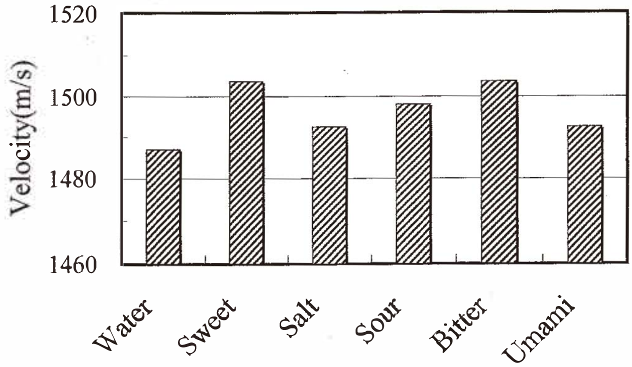

Fig. 1. Velocity of sound in water and in solutions of the five basic tastes (100 mM).

showed a similar tendency in sound velocities. However, some foods are mixtures of bitter solutions at a concentration of about 100 mM. We sense bitterness at concentrations less than 100 mM, and sense sweetness at concentrations higher than 100 mM. For practical taste sensing, the sound velocities may change from the values shown in Fig. 1. Therefore, these two tastes are easily identified. In acidic solutions and salty solutions, solutions which are both monovalent, the sound velocities are slightly different. In this case, differences between the ions of Na^+ and H^+ may be evident.

Figure 2 shows sound velocities in solutions with various concentrations of sweetness (sucrose). As the concentration increases, the sound velocity increases as well. On the other hand, sound velocities in water and in solutions with concentrations less than 1 mM are comparable. Therefore, the identification of those solutions on the basis of sound velocity is difficult. However, changes in sound velocities are detectable, because the sweetness threshold for humans is near 100 mM.

Practically, humans can sense complex tastes. We measured sound velocities in taste solutions which were mixtures of two kinds of solutions. Figure 3 shows one example of the results. We can see combinations of tastes that are known as the comparison effect and the counterbalancing effect. The sweet solution at 1 M and the salty solution at 1 M were used to evaluate the comparison effect. The mixture of 0.1 M sweet solution and 0.1 M bitter solution was used to evaluate the counterbalance effect. The solutions were mixed with the same concentrations. Each sound velocity in the single taste solution is shown in the figure for the sake of comparison. The velocity of sound in the mixed taste solutions shows a tendency different from the velocity of sound in single taste solutions. We could not identify which taste substances influence the sound velocities in these mixed taste solutions. We consider that the differences between the sound velocities are caused by the electrolytic characteristics of the two solutions. Sound velocity C in a liquid can be formulated as follows:

$$C = \sqrt{\frac{K}{\rho}}, \tag{1}$$

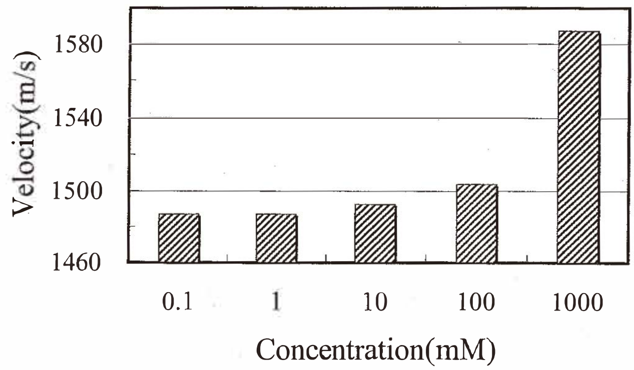

Fig. 2. Velocity of sound to density of sweetness solution (Sucrose).

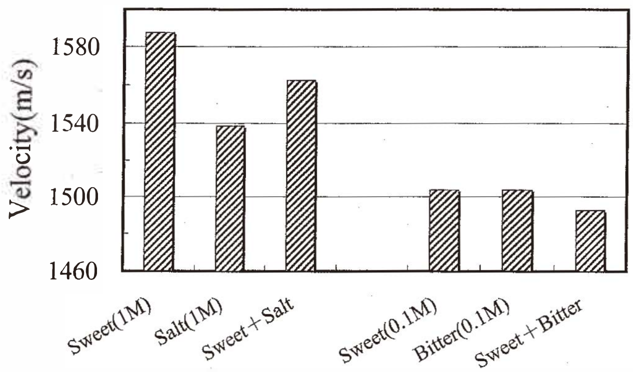

Fig. 3. Velocity of sound in mixed taste solution.

where K is bulk modulus and ρ is density. From this formula, it seems that differences in these values affect the mixed taste solutions. Therefore, there is a possibility that the interaction of the tastes can be expressed by an appropriate method using the velocity of ultrasonic sound. There is another effect called the synergy effect that describes the interaction of the tastes. The synergy effect appears when several kinds of umami substances are mixed. Further studies are necessary on this effect.

Many taste substances are included in marketed beverages. Sound velocities in four kinds of tea and two kinds of juice are shown in Fig. 4 and Fig. 5, respectively. The sound velocities in straight tea and in Earl Grey have values comparable to the velocity in water. Various taste substances may be mixed in the tea. As a result, the sound velocities in milk tea and in tea with lemon are higher than the sound velocities in straight tea. We cannot identify which taste substances influenced the sound velocities in these teas. However, many acidic elements and sweet elements may be present in the lemon tea. Many kinds of

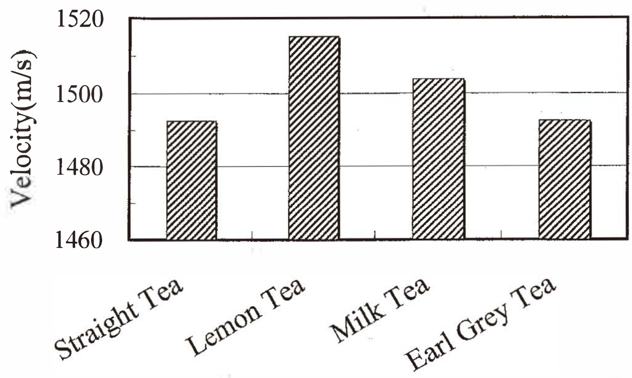

Fig. 4. Velocity of sound in beverages (tea) on the market.

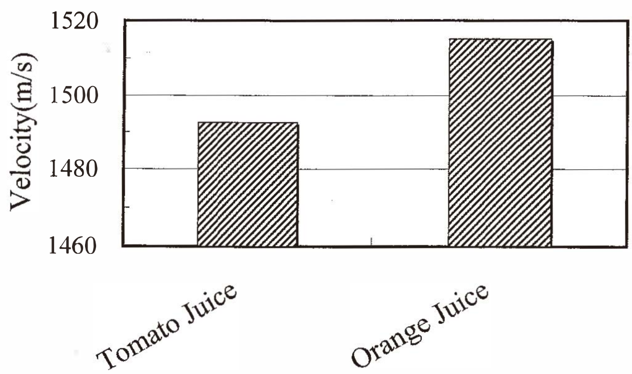

Fig. 5. Velocity of sound in beverages (juice) on the market.

milk fat are added to straight tea to make milk tea. Therefore, the differences among these elements may influence the sound velocity. If we compare tomato juice with orange juice, the sound velocities in these juices have obvious differences. When we drank the juice, we subjectively felt that the orange juice was sweeter than the tomato juice. In taste sensing by lipid membranes which has been reported, the performance of the sensors in detecting the sweetness of a solution is insufficient. By our method using ultrasonic sound, a result indicating the feasibility of detecting sucrose was obtained as shown in Fig. 1. and Fig. 2.

3. Experiment II

3.1 *Basic theory of resonance*

Recently, both theoretical and experimental studies of acoustic phonons have been carried out as part of research on mesoscopic superlattices (layered media), which are made by stacking atomic monolayers.[6–15] In these studies, frequencies of acoustic phonons range from several GHz to 1 THz. If we use frequencies of about several MHz, it is possible to consider that the same results occur using ultrasonic sound and layered media a few mm in size.

One part of the present study is to demonstrate the resonant transmission of acoustic phonons in superlattices using ultrasonic sound and layered metal media.

We show a basic system for the theoretical consideration of this experiment in Fig. 6. One free surface of the layered medium (LM) is immersed in liquid. The LM is made with solid bilayers AB which are stacked alternately. For simplicity, we assume that the acoustic impedance of the transducer is the same as those of the B layers. The ultrasonic sound is incident normal to the interfaces in the LM from one surface of the LM. After travelling through the LM, the ultrasonic sounds is transmitted to the liquid from the other LM surface, and a portion of the sound energy is reflected from the free surface back to the LM. Transmitted sound pressure in the liquid is measured by a hydrophone.

Figure 7(a) shows transmission rates of ultrasonic sound from the LM into water as a liquid, where material A is Cu with thickness 0.5 mm and material B is Ag with thickness 0.5 mm. The total number of solid bilayers is eight. The acoustic impedances of the system are 44.7 for Cu, 38.3 for Ag, and 1.48 for the water in units of 10^6 kg m^{-2}s^{-1}.

If we assume that the ultrasonic sound is a continuous wave, then there is a frequency (ν_R = 2.08 MHz) at which its transmission rate has a peak in spite of the large mismatch between the acoustic impedances of Cu and Ag with water. The water has a value less than one tenth of those of Cu and Ag. At this frequency ν_R, an infinite periodic layered medium has a stop band which suppresses transmission of the sound. However, a finite LM has a localized oscillation at the surface immersed in the water.[12] With this oscillation, the ultrasonic sound is efficiently transmitted from the LM into the water.[16] The time needed

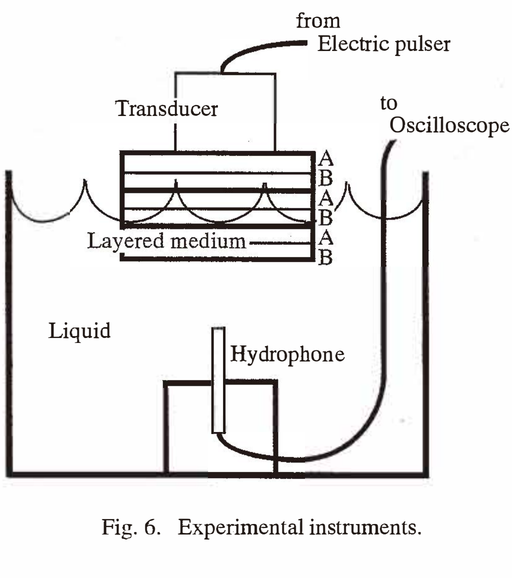

Fig. 6. Experimental instruments.

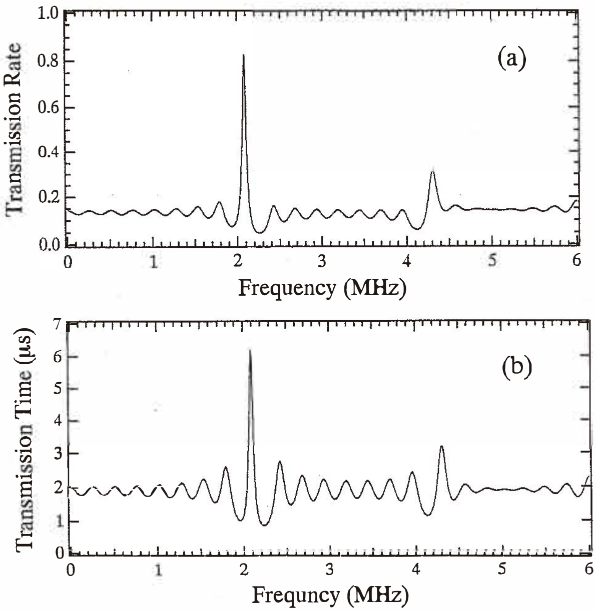

Fig. 7. (a) Transmission rate and (b) transmission time through Cu/Ag layered medium.

for the ultrasonic sound to pass through the LM at this resonance is longer than that in the case of nonresonance as in Fig. 7(b).

The above resonance transmission is applicable to acoustic impedance matching devices at the resonance frequency ν_R.

3.2 *Ultrasonic pulse transmission experiment*

In the above subsection, we assume that ultrasonic sound is a continuous wave. However, a pulsed wave is practical for applications of ultrasonic sound. In this section, an experiment using ultrasonic pulses is discussed.

When an ultrasonic pulse was incident onto the LM as shown in Fig. 6, sound pressures of the ultrasonic pulse in water were measured as in Fig. 8(a). The energy flux is calculated from the pressures in water and is shown in Fig. 8(b); it is proportional to the power spectrum of the pressures. For the sake of comparison, we replaced the LM with 8.0-mm-thick isotropic bulk Cu plate. With this configuration, the pressure in water and the energy flux became as shown in Figs. 9(a) and 9(b), respectively.

Incident ultrasonic pulses passing through the Cu plate penetrate gradually into the water with repeating reflections between the two surfaces of the Cu plate. This property is clearly evident in Fig. 9(a). If we can assume that the phases of the ultrasonic pulses do not change with the reflections, the power spectrum of the pressures (the energy flux) must have peaks at the same frequencies as those of the following function:

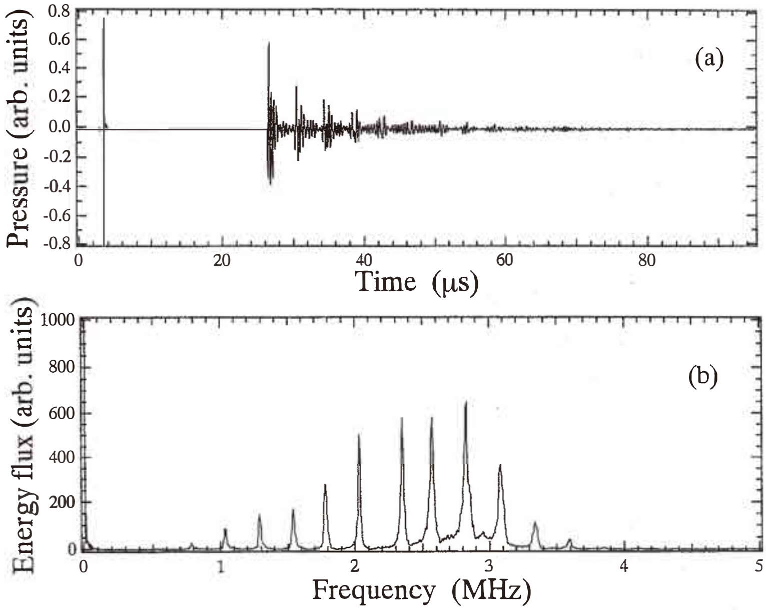

Fig. 8. (a) Sound pressures and (b) energy flux in water from Cu/Ag layered medium.

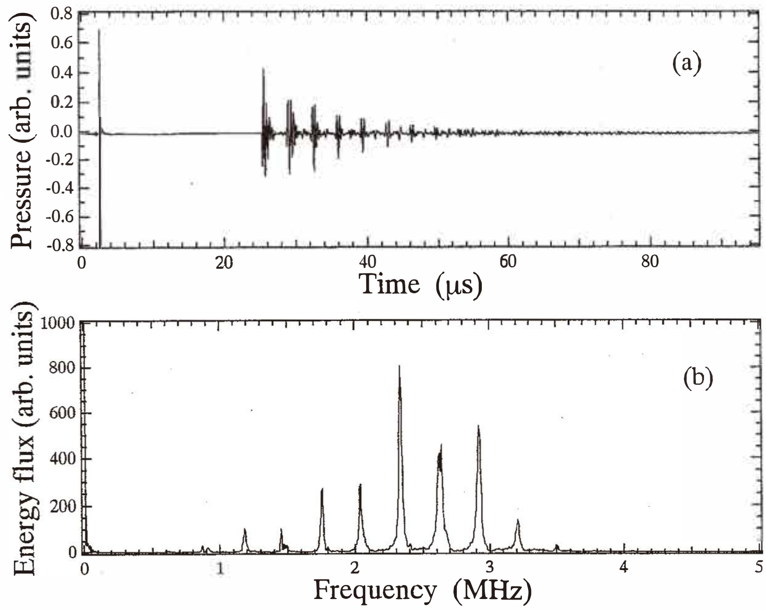

Fig. 9. (a) Sound pressures and (b) energy flux in water from an isotropic Cu plate.

$$|S(\nu)|^2 = \frac{\frac{1}{4}e^{\gamma}}{\sinh^2(\gamma/2) + \sin^2 \pi\nu\tau}, \quad (2)$$

where ν is frequency and γ is the damping rate of the pressure pulses in the water as shown in Fig. 9(a). From this function, we see that the peaks are separated by the same frequency interval $1/\tau$. The value of τ is calculated as 3.4 μs from Fig. 9(b). This value is almost the same as the theoretical value of 3.8 μs which is derived from the round trip time in the 8.0-mm-thick Cu plate.

Energy flux into the water from the LM is shown in Fig. 8(b). Peaks do not have the same frequency intervals. This implies that the pulse reflection is not simple and its travel time is different at the frequency shown in Fig. 7(b). However, near the resonance frequency ν_R, both energy fluxes in Fig. 8(b) and Fig. 9(b) have peaks. Further, peaks in the spectrum for the LM are at frequencies near the resonance frequency ν_R, when we compare Fig. 8(b) with Fig. 9(b). This feature resembles the drawing effect in the field of nonlinear phenomena.

4. Summary

We collected basic data on taste sensing using the velocities of ultrasonic sound in five basic taste solutions and two marketed beverages from experiment I. For realistic applications, we need more precise treatments. One method is to detect the absolute values of the energy flux of sound in the liquids. If this becomes possible, the damping characteristics of ultrasonic sound in liquids will help to distinguish the taste solutions precisely. To realize this, the hydrophone must be immersed in the taste solutions. In this case, we need ultrasonic sound to penetrate into the liquids more efficiently. Further, transducers must emit a stable sound spectrum which is not affected by loads, i.e., the kind of liquid. For this purpose, acoustic impedances should be matched sufficiently. However, transducers with a quarter-wave plate change their spectra if we replace the loads. To render the spectrum stable, it is feasible to use the LM discussed in experiment II, which is a constituent of rigid metals.

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