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Visualization of Changes in Taste of Food during Chewing Process

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Recently, food production technologies using a 3D food printer have been developed. A taste sensor is expected to be used for food design in such food production. In this study, as the first step toward food design, we attempted to visualize the changes in the taste of food during the chewing process using a model food of a *monaka* (a traditional Japanese sweet with a wafer coating) with a three-layer structure composed of three ingredients: a salty gel, mashed potato, and the wafer. The temporal changes in the six taste qualities of the model food, namely, saltiness, sweetness, umami, bitterness, sourness, and astringency, were analyzed. Sensory tests using the temporal dominance of sensation (TDS) method were performed at the same time. The difference in the release of chemicals associated with the tastes of the three ingredients with the number of times that they were mashed as a simulation of chewing was analyzed. We found that texture and bitterness were dominant in the wafer, saltiness was dominant in the salty gel, and umami was dominant in the mashed potato. The results of the sensory tests using the TDS method and those of the measurement using the taste sensor were in good agreement: the saltiness of the salty gel and mashed potato was perceived in the initial and middle stages of the chewing process, whereas the umami of the mashed potato was perceived from the middle stage onwards. Moreover, the texture of the wafer was perceived in the initial stage, whereas its bitterness and texture were perceived in the final stage. These findings indicate the possibility of visualizing the release of chemicals associated with taste along with the breakdown of food in the mouth using a taste sensor.

1. Introduction

Although humans sense the taste of food, the evaluation of taste in conventional sensory tests may be affected by the physical conditions and individual variations among panelists. Moreover, conventional sensory tests may be a significant burden to panelists. A taste sensor, or an electronic tongue, for the visualization and quantification of taste was developed 30 years ago. Its use has become widespread in the last 20 years, and it is now used by food and pharmaceutical

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companies.(1–5) A taste sensor can quantify astringency in addition to the five primary taste qualities, namely, sweetness, bitterness, saltiness, sourness, and umami. It can also measure aftertastes typified by *koku* (a Japanese word meaning "rich taste"), which is the aftertaste of umami.(6–9)

The taste sensor has been commercially available and used around the world. However, a taste sensor measures the taste of food in an equilibrium state, that is, a static state. Although the changes in the taste of medicinal tablets as they disintegrate in the mouth have been dynamically measured,(10) there have been no reports on measuring the changes in the taste of food with a more complicated taste structure in the mouth, such as sweets, *jiaozi* (dumplings), or hamburger steak.

People in some parts of the world have insufficient food, whereas a large amount of excess food is disposed of as food loss and waste in developed countries. One of the solutions to eliminating this imbalance is to reduce the food loss and waste by grinding unused ingredients into powder and granular materials and processing these materials using a 3D food printer.(11–14) This technique will also contribute to the establishment of a new food supply industry that offers food that is personalized in accordance with the preferences and physical conditions of individuals.(15) What is important in this technique is how accurately the taste, smell, and texture of real food are reproduced by the 3D food printer. In particular, the characteristics of the food manufactured using the 3D food printer should be as close as possible to the characteristics of real food during the chewing process in the mouth.

The taste sensor is expected to be used for food design in food production using a 3D food printer. With these ideas as a background, in this study, we attempted to visualize the changes in the taste of food during the chewing process using as a model food with a three-layer structure. *monaka* (a traditional Japanese sweet) composed of three ingredients: a salty gel, mashed potato, and the wafer. This is the first step toward food design.

The temporal changes in six taste qualities associated with the model food, namely, saltiness, sweetness, umami, bitterness, sourness, and astringency, were analyzed. Sensory tests were performed at the same time because the temporal changes in the taste qualities strongly depend on the chewing process in the mouth.

The temporal changes in the tastes of the salty gel, mashed potato, and wafer, i.e., the ingredients of the model food, associated with mashing as a simulation of chewing were successfully quantified by the measurement using the taste sensor (hereinafter referred to as "taste sensor measurement"). The changes in the taste of the model food reflected the changes in the taste of the salty gel and mashed potato. The sensory tests were performed using the temporal dominance of sensation (TDS) method. It was found that texture and bitterness were dominant in the wafer, saltiness was dominant in the salty gel, and umami was dominant in the mashed potato. The results of the taste sensor measurement and the sensory tests show that the saltiness of the salty gel and mashed potato was perceived in the initial and middle stages of the chewing process of the model food, whereas the umami of mashed potato was perceived from the middle stage onwards. The bitterness of the wafer was perceived in the final stage. These results will significantly contribute to food design in which the changes in taste in the mouth should be considered.

2 Materials and Methods

2.1 Taste sensor

A membrane composed of a lipid, a plasticizer, and a polymer (lipid/polymer membrane) served as the receptor for taste qualities in the taste sensor. Figure 1 shows the taste sensor (TS-5000Z: Intelligent Sensor Technology, Inc.) and its electrodes. The lipid/polymer membrane was attached to the hollow part of the probe of the working electrode. Ag/AgCl and saturated potassium chloride (KCl) were injected into both the working electrode and the reference electrode. The potential difference between the sensor electrode and the reference electrode was measured. The chemical compositions of the receptive membranes for the different taste qualities were the same as those in previous studies.[6–9] The sensor electrodes for the different taste qualities were purchased from Intelligent Sensor Technology, Inc.

Figure 2 shows the measurement procedure. First, the potential in the reference solution corresponding to saliva, which is nearly tasteless, was measured. Here, the potential is denoted as V_r. Next, the potential in the sample solution (V_s) was measured. The difference between the two potentials ($V_s - V_r$) is the normal potential response called the relative value. Then, the sensor electrode was lightly washed. The sensor electrode was then dipped into the reference solution again. At this time, the membrane had not returned to the initial state because the chemicals associated with taste qualities with hydrophobic properties, such as bitterness, astringency, and umami, were still adsorbed on the membrane. As a result, the potential generated (V'_r) was different from that in the initial reference solution (V_r). The difference between this potential and the initial potential ($V'_r - V_r$) indicates the change in membrane potential caused by the adsorption of chemical substances onto the membrane (CPA value). The

Fig. 1. (Color online) Taste-sensing system (TS-5000Z: Intelligent Sensor Technology, Inc.) and its working and reference electrodes.

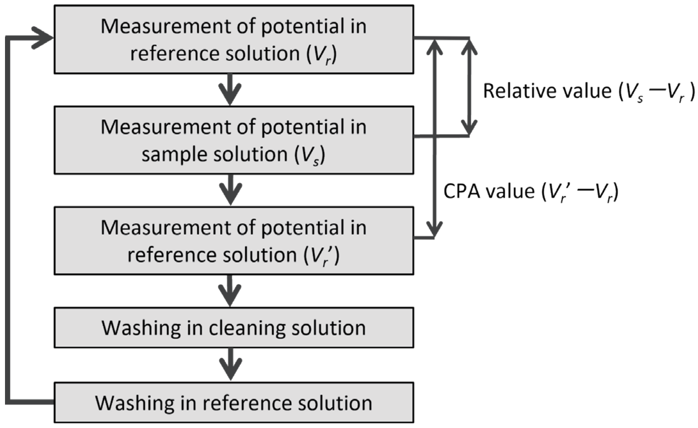

Fig. 2. (Color online) Measurement procedure using taste sensor.

CPA value corresponds to the aftertaste perceived by humans. The CPA value depends on the amount of chemicals associated with taste qualities adsorbed onto the membrane and the state of charge of the membrane.(16) As the final step in the measurement of a sample solution, the membrane was washed thoroughly in a specific cleansing solution to desorb the adsorbed chemicals associated with taste qualities and return the membrane to the initial state. Generally, this procedure (rotation) was repeated three to five times to quantify the change in taste of the sample solution. The average of the second to fourth measurement cycles was calculated as the response value. The standard deviations were calculated from these three cycles (n = 3) in the same way as in previous studies.(6–9,16,17)

As in human taste sensation, the voltage output of the taste sensor is proportional to the logarithm of the concentration of chemical substances including amino acids.(3,7,9,17) Namely, it follows the Weber–Fechner law.(18,19) Therefore, the sensor output can be converted by a linear transformation into the strength of the taste perceived by humans. Because humans can distinguish between two taste strengths with at least a 1.2-fold difference between them, 1.2 is used as a unit corresponding to the minimum difference in taste that humans can detect. The concentration is expressed as a power (1.2^n). Therefore, an increase in concentration by one order of magnitude is equivalent to an increase of 12.6 units. The potential output from the taste sensor can be converted into this unit. One unit of estimated taste strength is the minimum difference in taste that humans are able to detect.

The measurements described above were performed in cooperation with Taste & Aroma Strategic Research Institute Co., Ltd.

2.2 Experimental samples

The amounts of ingredients making up the model food (total weight of 4.95 g) with the three-layer structure used in the experiment were as follows: 1.95 g of salty gel, 2.40 g of mashed potato, and 0.60 g of wafer. The model food was subjected to taste sensor measurement and sensory tests. The variety of potato used was May Queen. A Taneraku A01wafer

(Kagadaneshokuhinkogyo Co., Ltd.) was used. The salty gel was prepared by mixing three components (amounts expressed as per 100 mL of water): 1.50 g of iota-carrageenan (Unitec Foods Co., Ltd.), 0.03 g of xanthan gum, and 1.25 g of NaCl. Figure 3 shows the three-layer structure (approx. 30 mm diameter and 15 mm height) of the model food. The top layer was the mashed potato, the middle layer was the salty gel, and the bottom layer was the wafer. The samples subjected to the taste sensor measurement should be in the form of a solution; moreover the sample quantity of at least 100 mL was necessary. Therefore, the model food of the quantity of 7.69–7.70 times of one model food 4.95 g was mashed in a tasteless solution (135 g) with the composition shown in Table 1; as a result, 38.08 g of the the model food was diluted by a factor of 4.55. This ratio was most suitable for the measurement, because when the dilution ratio is too high, the taste strength obtained in the measurement becomes small. On the contrary, if the ratio is low, the measurement becomes difficult because the viscosity of the sample became higher. Moreover, each ingredient was separately subjected to the taste sensor measurement. In doing so, the dilution ratio among the ingredients was maintained at the same value as that in the three-layer structure (salty gel:mashed potato:wafer = 10.0:8.31:30.25). Tartaric acid, monosodium glutamate (MSG), and tannic acid, as listed in Table 1, were purchased from Kanto Chemical Co., Inc. (Tokyo, Japan), sucrose, KCl, and quinine hydrochloride from FUJIFILM Wako Pure Chemical Corp, and iso-α acid (Kalsec) from Intelligent Sensor Technology, Inc.

Figure 4 shows the procedure for preparing the sample solutions of the model food and the three ingredients (four types of sample in total) that were subjected to the taste sensor measurement. First, the tasteless solution was heated to approximately 40 °C in a thermostatic

Fig. 3. (Color online) Three-layer structure of model food composed of mashed potato, salty gel, and wafer.

Table 1
Composition of tasteless solution used as solvent.

Taste sample	Reagents	Concentration
Sourness	Tartaric acid	0.3 mM
Sweetness	Sucrose	30 mM
Saltiness	KCl	10 mM
Umami	MSG	1 mM
Astringency	Tannic acid	0.005 wt%
Bitterness 1	Iso-α acid	0.001 vol%
Bitterness 2	Quinine hydrochloride	0.01 mM

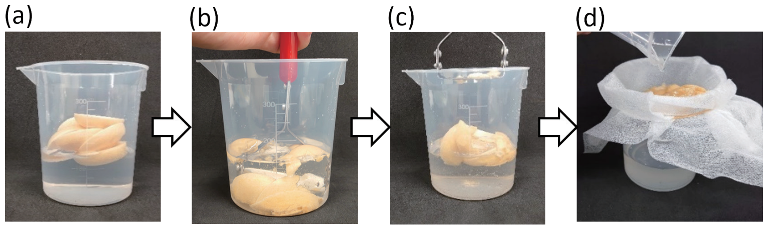

Fig. 4. (Color online) Procedure for preparing measurement samples: (a) pour tasteless solution, (b) mash sample to bottom, (c) lift up masher, and (d) natural filtration of mixture.

chamber. Each of the types of sample (model food, salty gel, mashed potato, and wafer) was placed in a 300 ml sample cup (7 cm inner diameter at the bottom) at an amount that maintains the above-mentioned dilution ratio [Fig. 4(a)]. Then, 135 g of the tasteless solution was poured into the sample cup. Then, the sample was mashed using a masher (4.5 cm diameter) for a given number of times (0, 1, 5, 10, 15, 20, 25, and 30 times) at a rate of once per second [Figs. 4(b) and 4(c)]. Finally, the mixture was naturally filtered through a nonwoven fabric (a piece of Bemcot M-3II separated into a single layer) and subjected to measurements [Fig. 4(d)].

2.3 Sensory tests

The sensory tests were performed on the model food by the TDS method. Two sensory tests were performed: one on three attributes (mashed potato, salty gel, and wafer) and the other on eight attributes (sweetness, umami, saltiness, bitterness, sourness, astringency, smell, and texture). The former sensory test was performed three times by each of six panelists, and the latter sensory test was performed three times by each of five panelists. The lowest significant proportion values (α = 0.05), Ps, were 0.52 and 0.265 in the former and latter sensory tests, respectively.[20] The chance level, which is the dominance rate that an attribute is obtained by chance, in the former sensory test was 0.33 and that in the latter sensory test was 0.125.

These sensory tests were performed by Taste & Aroma Strategic Research Institute Co., Ltd. The panelists were asked to assess which attribute was perceived to be dominant while looking at a computer screen that presented the complete list of attributes. The dominant sensory perception refers to the most striking perception at a given time.[20] Well-trained panelists with the ability to detect taste substances with high sensitivity were selected and enrolled in this study. These panelists also received training about once a week before the start of the study.

3. Results and Discussion

Figure 5 shows the changes in the taste of the model food, salty gel, mashed potato, and wafer with increasing number of times of mashing as measured using the taste sensor. The results are presented as the estimated taste strength from the sensor output, taking values at zero number of times of mashing as the origin. Negative changes mean the measured samples are tasteless. Hence, we focus on the positive changes hereafter. The figure shows that the first tastes detected were bitterness, astringency, sweetness, umami, saltiness, and sourness. Aftertaste, represented

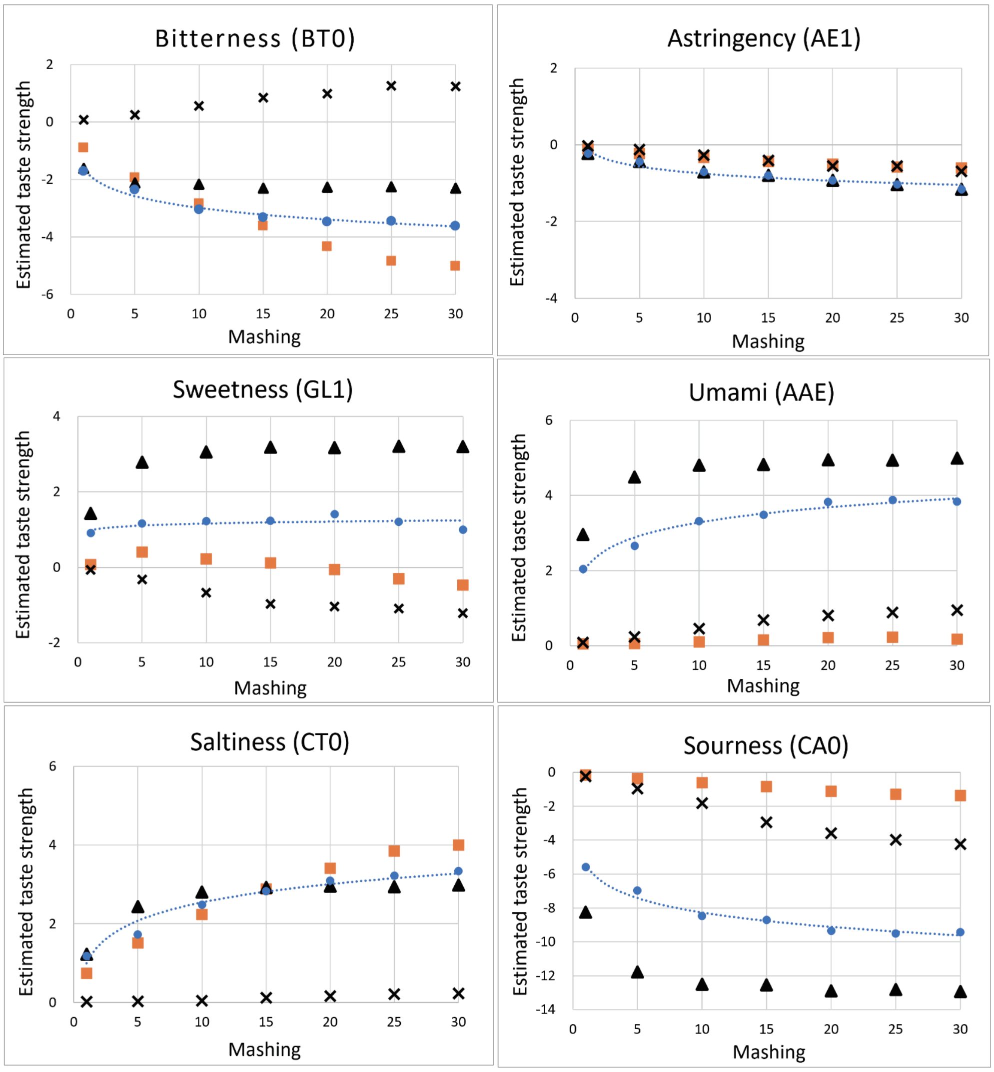

Fig. 5. (Color) Changes in taste of salty gel (■), mashed potato (▲), wafer (×), and model food (●) with the number of times of mashing. Each figure shows one of the six taste qualities: bitterness, astringency, sweetness, umami, saltiness, and sourness.

by CPA values, was negligible for all taste qualities. The names of the electrodes (BT0, AE1, etc.) are indicated next to the taste qualities.[(6–9)] The standard deviations for, e.g., saltiness and umami of the model food were (0.02, 0.02, 0.02, 0.01, 0.03, 0.00, 0.02) and (0.05, 0.08, 0.10, 0.10, 0.13, 0.09, 0.10), respectively, for the number of times of mashing (1, 5, 10, 15, 20, 25, 30 times) in this order.

The results indicate that the change in bitterness occurred in only the wafer, and those in astringency were small in the three ingredients and model food, whereas a relatively large change to the negative direction was observed in sourness. However, the corresponding change from pH 4.3 to 5.2 in the model food was a pH shift toward neutral, which is not recognized as a change in sourness by humans. Similarly, the change from pH 4.4 to 5.4 in the mashed potato, the change from pH 4.2 to 4.7 in the wafer, and the change from pH 4.2 to 4.4 in the salty gel were not detected as changes in sourness by humans. Changes in two taste qualities, umami and saltiness, were observed in the model food. As shown in Fig. 5, the estimated umami taste strength increased to approximately 4 after mashing 30 times, and saltiness taste strength increased from 0 to 3.3. According to the figure, umami was detected in the mashed potato and saltiness was detected in both the salty gel and mashed potato.

Although the change in taste was significant, as shown by the curves for umami and saltiness of the model food, the curves for the model food asymptotically approached the curves for the salty gel or mashed potato, which showed the largest change among the three ingredients. This tendency was observed for almost all taste qualities. The release of chemicals associated with taste was more rapid in single ingredients because they were in direct contact with the tasteless solution. As a result, the change in taste was more rapid and greater. The release of chemicals associated with taste was slower in the model food because each ingredient was not in direct contact with the tasteless solution.

Figure 6 shows radar charts of the estimated strengths of saltiness, umami, sweetness, astringency, and bitterness in the salty gel, wafer, mashed potato, and model food. Only the data

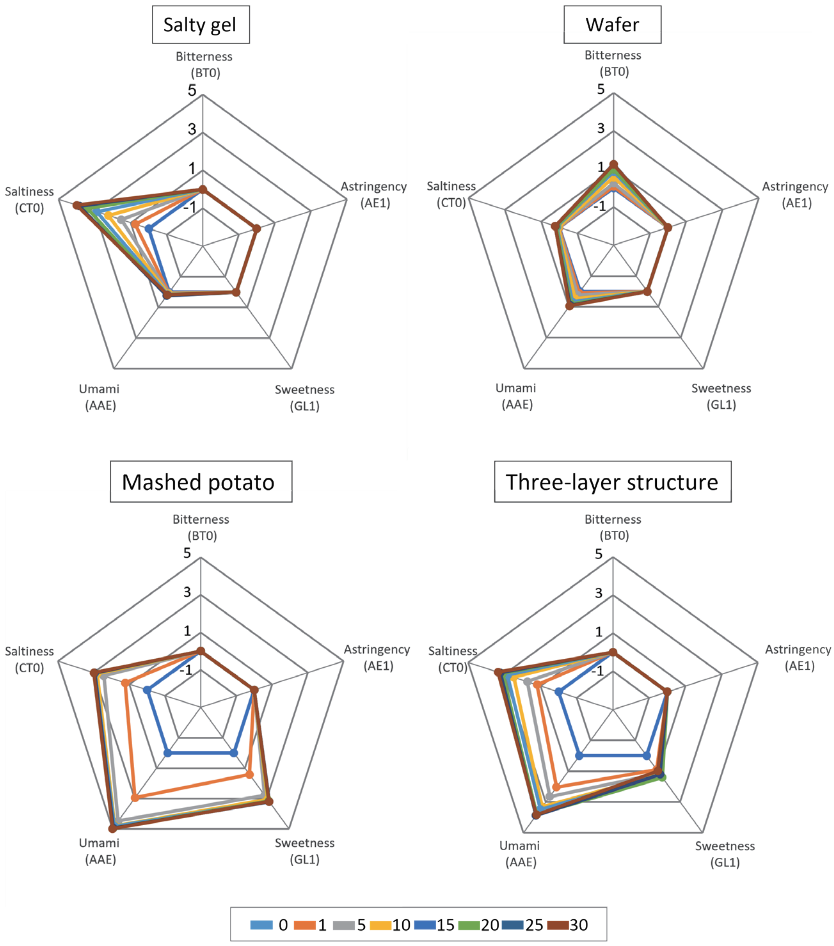

Fig. 6. (Color) Rader charts representing changes in five taste qualities.

on the taste strength greater than that of the tasteless solution are shown because a taste strength less than or equal to that of the tasteless solution is not recognized by humans. The figure shows that chemicals associated with saltiness were released from the salty gel with increasing number of times of mashing. Chemicals associated with taste were released more rapidly from the mashed potato than from the salty gel. Saltiness, umami, and sweetness were strongly perceived in the mashed potato. Only bitterness was perceived in the wafer, while considerably weak umami was detected. The strengths of other taste qualities were low and the changes in these taste qualities associated with the number of times of mashing were negligible in the wafer. From these results, we consider that the change in the taste of the model food was mainly due to changes in saltiness and umami, reflecting the changes in the taste of the salty gel and mashed potato, as indicated by the shapes of the radar charts.

Figure 7 shows the results of the sensory tests using the TDS method. One sensory test was performed on three attributes: mashed potato, salty gel, and wafer [Fig. 7(a)]. The wafer was the

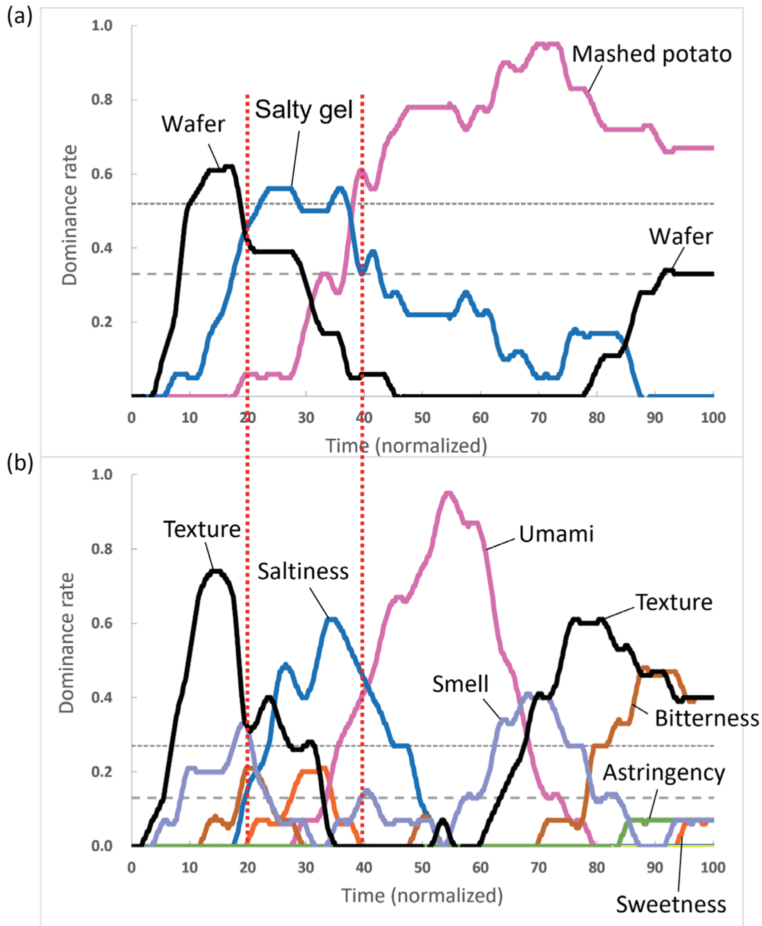

Fig. 7. (Color) Results of sensory tests using TDS method on (a) three attributes and (b) eight attributes. *Ps* and the chance level are indicated by the dotted and broken lines, respectively. Wafer and texture are shown in black, salty gel and saltiness in blue, mashed potato and umami in pink, bitterness in brown, smell in purple, and astringency in green.

dominant attribute, followed by the salty gel, in the initial stage of the chewing process for approximately 5 s before the model food was swallowed. The mashed potato was the dominant attribute in the middle and final stages, and the wafer began to be perceived in the last part of the final stage.

The other sensory test was performed on eight attributes: sweetness, umami, saltiness, bitterness, sourness, astringency, smell, and texture [Fig. 7(b)]. Texture was dominant, followed by saltiness, in the initial stage. Umami was dominant in the middle stage. Smell, texture, and bitterness were dominant in the final stage. In other words, while only one or two attributes were perceived in the initial stage, multiple attributes were perceived in the final stage of the chewing process.

Figure 7 shows that texture was dominant for the wafer. This result agreed with the extremely low taste strength of the wafer indicated by the taste sensor. Figure 7 also shows that saltiness and umami were dominant in the salty gel and mashed potato, respectively. These results were consistent with those of the taste sensor measurement shown in Fig. 6.

Let us consider why the texture of the wafer was dominant in the initial stage of the sensory tests. Humans sense taste and texture mainly through the tongue. The wafer was in direct contact with the tongue because it was the bottom layer of the model food. This appeared to be the reason why the texture of the wafer became dominant in the initial stage. In fact, the texture lost its dominance, and multiple tastes and smells were perceived instead as the chewing process proceeded. Then, the texture of the wafer clinging to the tongue and the bitterness of the wafer became dominant again in the final stage after the ingredients were ground by the chewing process and the mashed potato and salty gel were swallowed. Bitterness was the specific taste of the wafer as shown in Fig. 6.

As explained above, the results of the taste sensor measurement shown in Figs. 5 and 6 were in reasonable agreement with the results of the sensory tests shown in Fig. 7. However, it is not easy to simply compare these results with respect to time because the chewing process in the mouth (Fig. 7) does not have a one-to-one correspondence with the number of times of mashing in the taste sensor measurement. Another difference between the chewing process and the conditions in the taste sensor measurement is that small ingredients may be swallowed during chewing. Despite these differences, the results of the taste sensor measurement show that chemicals associated with saltiness and umami were released gradually, consistent with the results of the sensory tests. In the TDS method, the relative dominance of each attribute is evaluated out of a total of 100%, and the absolute strength of each attribute is not evaluated. The taste strength is generally low in the initial stage, increases in the middle stage, and decreases in the final stage.[21–23] On the basis of these findings, it is necessary to develop a method of evaluating the change in taste during the chewing process while ensuring consistency with the results of the taste sensor measurement.

The results of the sensory test show that texture and smell are also important in addition to taste. The establishment of a measuring technique for visualizing these attributes is important. It is essential to further clarify the phenomena occurring during the chewing process and to ensure consistency between the conditions during the chewing process and those in the taste sensor measurement. Once such a technique is established, it will enable the visualization of changes in the taste of many foods during the chewing process.

4. Conclusions

In this study, we attempted to visualize the changes in the taste of food during the chewing process using a model food with a three-layer structure consisting of a salty gel, mashed potato, and wafer. The results of the taste sensor measurement showed that chemicals associated with saltiness were gradually released from the salty gel with increasing number of times of mashing (30 times in total) when the salty gel was subjected to the measurement as a single ingredient. The release of chemicals associated with taste from the mashed potato was more rapid than from the salty gel. Saltiness, umami, and sweetness were dominant in the mashed potato. Only bitterness was perceived in the wafer. The changes in the taste of the model food reflected the changes in the taste of the salty gel and mashed potato.

Sensory tests were performed on the model food by the TDS method. One sensory test was performed on three attributes: mashed potato, salty gel, and wafer. The wafer was the dominant attribute, followed by the salty gel, in the initial stage of the chewing process for approximately 5 s before the model food was swallowed. The mashed potato was the dominant attribute in the middle and final stages, and the wafer began to be perceived in the last part of the final stage. A second sensory test was performed on eight attributes: sweetness, umami, saltiness, bitterness, sourness, astringency, smell, and texture. Texture was found to be dominant, followed by saltiness, in the initial stage. Umami was dominant in the middle stage. Smell, texture, and bitterness were dominant in the final stage. Comparing the results of the two sensory tests, we found that texture and bitterness were dominant in the wafer, saltiness was dominant in the salty gel, and umami was dominant in the mashed potato.

The results of the sensory tests using the TDS method and those of the taste sensor measurement were in good agreement: saltiness of the salty gel and mashed potato was perceived in the initial and middle stages, whereas umami of the mashed potato was perceived from the middle stage onwards. Moreover, the taste of the wafer was weak and the wafer texture was mainly perceived by the panelists. However, the bitterness and texture of the wafer were perceived in the final stage of the chewing process of the model food. These results indicate the possibility of visualizing the release of chemicals associated with taste along with the breakdown of food in the mouth using the taste sensor, which will significantly contribute to food design.

Acknowledgments

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