An Intra-Oral Interface to Affect a Taste Change Continuously by Using Electrical Stimulation with Periodic Intervals

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Abstract: Recently, increasing attention has been paid to the health impacts and lifestyle diseases due to the excessive intake of salt and sugar. To address this problem, there have been studies to control taste by the electrical stimulation of food and drink through tableware. However, it is not possible to realize a change of taste during the chewing food and drinking with this approach. Therefore, we consider that a change of taste is also required during chewing in order to achieve satisfied consumption. In this study, we develop an intra-oral interface to effect a taste change continuously by using electrical stimulation. We performed preliminary experiments to measure the sensitivity of the tongue by the position and area of an electrode. Then, we developed an interface to take into account the results of the experiments. We confirmed the effectiveness of the proposed interface through experiments examining the intensity of taste when using the developed interface. Moreover, by having periodic intervals to electrical stimulation by the PWM control, the proposed interface was confirmed to improve the intensity of taste continuously.

Key Words: electrical taste, intra-oral interface, human interface.

1. Introduction

Food has three properties: 1) nutrition, 2) palatability and 3) functional effects. Nutrition is a feature related to the production of energy and life support. Palatability represents personal preferences such as the taste, smell, color and texture of foods. Functional effects bioregulatory influences human conditions such as disease prevention and anti-aging. In the historical background of food, nutrition and functional effects properties were focused on 100 years ago to prevent starvation and develop a physique. However, in the period of satiation of recent years, there is a tendency toward palatability being a higher priority than the other properties [1]. Consequently, nutrition and functional effects properties are neglected, and problems with nutrition have occurred. For instance, there are lifestyle-related diseases due to the excessive intake of salt and sugar.

The most popular method to solve these problems is by reducing food intake, but there are also studies to control the taste (i.e. palatability) by using electrical stimulation to food and drink through tableware [2]. With this approach, it is not possible to realize a change of taste during chewing food and drinking. Behavior during meals is not only confined to the moment when food and drink enter the mouth but also includes the chewing food and drinking. Therefore, we propose an intra-oral interface to satisfy palatability and effect a taste change continuously by using electrical stimulation.

2. Related Work

2.1 Research of Taste in Information Science

“Taste” is not only the feeling on the tongue but also the fragrance, texture, temperature, color and sound of food and drink. Illusions can be delivered to the brain by presenting stimulation to other sense organs, making it possible to change the taste. By using this property, Koizumi et al. [3] reported to extend the texture of food by using sound inorder to enhance high and low frequencies of chewing sound. Narumi et al. [4] studied that satiety sensation was changed by visual size of the food. These studies influence the feeling of satisfaction of meal by giving a stimulus to sense organs other than taste, however, this paper provides a taste change to present only taste. Iwata et al. [5] used some property of illusions that reproduced a realistic meal by presenting a stimulus to the touch, taste and hearing. This research has a high affinity with this paper in terms of controlling the feeling of satisfaction of the meal. However, this paper provides a change in the “taste” without using chemicals.

2.2 Research of Electrical Taste

The electrical taste was discovered by Sulzer in 1754. Subsequently, various studies including Volta provided for research in the field of electrical taste [6]. Technically, the anode stimulation is more sensitive than the cathode stimulus in presenting electrical stimulation on the tongue. The anode stimulation tastes sour, salty and metallic, and the cathode stimulation tastes bitter [7]. Moreover, Thomas et al. indicate the cathode stimulation effects of inhibiting the salty taste [8]. There are some studies that investigate age differences, sex differences,
the laterality of the tongue, the usage of a metallic crown for dental treatment, and the presence or absence of smoke. Among these differences, there is a difference only in the age difference when estimating the threshold value of the electrical taste [9]. Using these features, some studies extended the palatability by using electrical stimulation to prevent the excessive intake of salt [2],[7]. These approaches realized a taste change by using electrical stimulation and could control palatability without a changing nutritional value as shown in Fig. 1. It is possible to add electrical stimulation during contact with tableware, but it is important to continuously taste the induced changes during the eating and drinking period.

Hence, we propose an intra-oral interface to effect a taste change continuously during chewing. In addition, we further discuss the taste change in chewing food by using electrical stimulation while comparing the previous method [2] to the proposed method. Moreover, we also discuss the intensity of taste in chewing food by made a comparison between a method of electrical stimulation with a certain value from the beginning to the end and a method of having periodic intervals to electrical stimulation by the PWM control.

3. The Proposed Method

It is necessary to determine the position and the area to install an electrode for electrical stimulation. In this section, we describe an overview of the proposed method to develop the intra-oral interface in Fig. 2.

3.1 Output of Electrical Stimulation

3.1.1 Electrical stimulation to human body

The safety standard that medical devices comply with when presenting electricity to the human body is not to induce ventricular fibrillation. The current to accomplish this standard is referred to as the maximum allowable current. The factors to determine the maximum allowable current are the current value, the duration time, the route through the body, and the waveform [10]. Figure 3 shows the safe and dangerous zones of the levels defined by physiological influence shown in Table 1 when DC current is passed through the human body to both feet from the left hand. The maximum current value to be used in this study is 2 mA in consideration of the safety of the human body from the DC-1 region in Fig. 3. The current route through the body is determined in consideration of Table 2. The heart current coefficient \( F \) is derived from the current value of the standard current route \( I_h \) (both legs from left hand) and the current value of the utilized current route \( I_{th} \) as follows:

\[
F = \frac{I_h}{I_{th}} \tag{1}
\]

For example, it can be said that a current of value of 0.1 mA along the standard current route and a current of value 0.077 mA along the used current route (from chest to right hand) have an equivalent risk. The mouth is on the extension line of the chest, and the heart does not lie on the path between the mouth and the right hand. Therefore, the heart current coefficient when the current route passes from the mouth to the right hand is considered similar to the coefficient in the case of right hand from chest. Consequently, we determined that the current route to use is to the right hand from the mouth. The electrical stimulation is employed only via an anode using direct current with consideration given to the safety of the human body.
3.1.2 The way of presentation to the intra-oral area

There are two methods that present the change of taste to the tongue by electrical stimulation. One is to present electrical stimulation to the food [2]. The other is to directly stimulate the tongue while eating food and drinking. The previous method [2] used electrical stimulation through foods to the tongue. Therefore, the presented electrical value is lower due to the resistance in the foods. Consequently, the change of taste is lower than expected. The previous method cannot control the electrode area because the foods work as the electrode to the tongue, which means the change of taste is not constant. For these reasons, we determined to apply electrical stimulation directly to the tongue during eating and drinking. Silver was chosen as the material for the electrode because it has high thermal and electrical conductivity.

3.2 The Sensitivity of Tongue by Position

This section describes the measurement of sensitivity distribution on the tongue by electrical stimulation in order to determine the suitable position for the electrode. Humans perceive taste by contacting foods in saliva and via sensory organs called taste buds in the papilla [11]. There are several types of papillae on the tongue. The fungiform papillae are mapped from the tip to the center. The circumvallate papillae are located in the back of the tongue. The foliate papillae exist on the sides of the tongue. Each papilla has a different shape. The taste buds in the papilla exhibit the same characteristics, but the number of taste buds is different. Shawn et al. have demonstrated the relationship between the number of taste buds and the sensitivities at the tip, center, and sides of the tongue [12].

In this paper, we took into account the previous work that found no difference in the electrical sensitivity of laterality [9]. We designed a half-model of the test interface to present electrical stimulation as shown in Fig. 4. The size of test interface is 55 mm in length, 25 mm in width, 10 mm in height, and 5 g. The interface is made of ABS (Acrylonitrile Butadiene Styrene) material. In Section 3.4, we discuss experiments performed to determine the electrical sensitivity on the tongue by position as well as the most effective position to present the taste change by electrical stimulation.

3.3 The Sensitivity of Tongue by Area

The study that related the stimulation area and the sensitivity on the tongue by using chemical substances confirmed that the sensitivity on the tongue was higher when the stimulation area was smaller [13]. Another study that compared the number of papilla with the taste threshold by using a chemical substance verified that they are related proportionally [14]. Therefore, these results indicate the relationship between the electrical density and the sensitivity of the tongue. The electrical density; \( j \) can be expressed by the following equation,

\[
j = \frac{I}{S} \tag{2}
\]

where \( I \) is the current and \( S \) is the electrode area.

The current threshold becomes lower when the electrode area is smaller. The lower current value is used for safety purposes. This paper used a smaller electrode area to present a maximized change of taste.

3.4 Pre-Experiments That Measures the Sensitivity of Tongue by Position and Electrode Area

3.4.1 Produces

The purpose of this experiment is to determine the minimum current value at which humans can perceive electrical stimulation at different positions and areas. These parameters are used to develop the intra-oral interface. We take into account the distribution of taste buds and the shape of the papilla to arrange the electrodes on the tongue as shown in Fig. 4 ((a)–(h) are the electrode positions and (a), (b), and (e) are located on the side). The electrode areas are 0.5 \( \text{mm}^2 \), 12.5 \( \text{mm}^2 \), and 50 \( \text{mm}^2 \). This experiment is carried out on three subjects. All the subjects received explanations of the procedures and possible risks of the experiments, and gave written informed consent to participate in the experiments. The experimental procedure is as follows:

(i) We provide electrical stimulation that the subject’s tongue can perceive for learning (the provided electrical stimulation is 0.3 mA–2 mA).

(ii) The current is lowered gradually from the learned current value until the subjects cannot perceive the electrical stimulation.

(iii) This determines the minimum electrical stimulation if there is an obvious response two out of three times in repeating the stimulation. This value is regarded as the minimum threshold.

These processes are conducted 24 times in different combinations of position and area. The time and the interval of the presented electrical stimulation are 1 s.

3.4.2 Result

Figures 5–15 show the results of the experiments. The experimental results of area and position are shown separately in order to more easily compare them. Subjects are excluded from the results when the subject cannot perceive the maximum current (2 mA) on the tongue.

(1) Threshold of electrical stimulation related to a presented electrode position

Figures 5–7 are provided separately for comparison purposes. The vertical axis represents the current values, and the horizontal axis identifies the position tested. The threshold values of the tongue tip and edge ((a), (b), (c), (d), (e), and (f)) tend to be lower. The center and back of the tongue ((g) and (h)) tend to exhibit a higher threshold. Moreover, the sides of the tongue ((a), (b), and (e)) have lower thresholds than the upper surface ((c), (d), and (f)). The position with the lowest threshold is the...
tip of the tongue ((e) and (f)), which is lower than the edge of the tongue ((b) and (d)). Consequently, the higher sensitivities are spread over the lingual margin from the tip of the tongue. Therefore, we designed the intra-oral interface of which electrode is set from tip to edge of the tongue.

(2) Threshold of electrical stimulation related to a presented electrode area
Figures 8–15 are provided separately for comparison purposes. The vertical axis represents the current values, and the horizontal axis shows the size of the electrode area. Black lines indicate the average value of subjects.

The results show that the threshold tends to be lower when the size of the area is smaller. There are some cases where the threshold with 12.5 mm$^2$ was lower than with 50 mm$^2$. However, when comparing the average value of subjects, 0.5 mm$^2$ exhibited the lowest threshold across all positions. Hence, the intra-oral interface utilizes an electrode area of 0.5 mm$^2$.

3.5 Mechanism of Interface of Proposed Method
The proposed method uses electrical stimulation directly from the anode to the tongue as shown in Fig. 16. It affects a change in taste continuously while drinking. The electrical stimulation utilizes direct current. The maximum current is 2 mA, and the voltage is 1 V. The electrode is made of silver. The electrode is located from the tip to the edge of the tongue and has an area of 0.5 mm$^2$. The size of the developed interface is 70 mm in length, 35 mm in width, 15 mm in height, and 5 g. The frame of the interface is made of EVA (Ethylene-vinyl Acetate copolymer). The number of electrodes is five as shown in Fig. 16 (b). The details of the mechanism are shown in Fig. 16 (c). The interface is set on the intra-oral area in order to effect a change in taste. The right hand touches the cathode. The vari-
able resistance is used for setting the current, and PWM control circuit works to control the duty ratio that used for Section 5.

In order to install the interface in the oral area, there are concerns about differences in the shape of the tongue and insufficient contact depending on the size of the electrode. By using EVA, which is a flexible material, the developed interface avoids the misalignment and adjusts to each human’s tongue. Also, larger electrodes prevent the flexibility of the material because the electrode is made of metal. In the developed interface, we employ small electrodes that not only have better sensitivity described in Section 3.4.2 but also maintain flexibility. Moreover, by arranging a number of electrodes to increase the number of contact points, poor contact is prevented in the proposed design.

4. Experiment to Affect Taste Change Continuously
In this section, we compare the proposed interface with the previous approach [2] in order to evaluate the experiments by the both methods on equal terms. The purpose of the experiments is to clarify whether or not the proposed method affects the change in taste while drinking.

4.1 Procedure
This experiment uses sports drink (Produced by Otsuka Pharmaceutical Co., Ltd. Nutritional information amount per 100 ml: Calories 25 kcal, Protein 0 g, Fat 0 g, Carb 6.2 g, Sodium 49 mg, Potassium 20 mg, Calcium 2 mg, Magnesium 0.6 mg). The current is 2 mA for both the proposed method and the previous method.

The subjects evaluate the taste of the drink that is included in mouth without electrical stimulation [before addition], the drink that is included in mouth with electrical stimulation [addition], and chewing with electrical stimulation [drinking]. Each subject evaluates quality of taste according to the six-grade system [0: Not perceived at all, 1: Weakly perceived, 2: Slightly weakly perceived, 3: Normally perceived, 4: Slightly strongly perceived, 5: Strongly perceived] concerning five taste types [Sweet, Bitter, Sour, Salt, Metallic]. This experiment is carried out with five subjects. All the subjects received explanations of the procedures and possible risks of the experiments and gave written informed consent to participate in the experiments. Figure 17 is the condition of this experiment.

4.2 Results and Discussions
Figures 18–22 present the average evaluation values of all the taste types for both the previous method and the proposed method at the three timings (before addition: the drink that is included in mouth without electrical stimulation, addition: the drink that is included in mouth with electrical stimulation, and drinking: chewing with electrical stimulation).

The proposed method compared with the previous method shows a tendency to affect a change in taste of salty and metal-
lic perceptions continuously during drinking. It is assumed that drinking with electrical stimulation affects the change in taste in the same way as the drink that is included in mouth with electrical stimulation. We evaluated statistically significant differences. The paired t-test technique (two-sided) was employed to verify the results. The t-test was computed from Figs. 20 and 22. From the t-test for Salty in Fig. 20, we determined whether there is a statistically significant difference for before addition-addition – t(4) = −2.359, p < 0.078 and before addition-drinking – t(4) = −1.000, p < 0.3739 and for proposed method: before addition-addition – t(4) = −6.325, p < 0.003 and before addition-drinking – t(4) = −6.325, p < 0.003. Therefore, significant differences were observed in the proposed method, however, in the previous method, no significant difference was observed. From these results, it could be confirmed that the interface of the proposed approach could affect a change in taste continuously during drinking. In addition, there is a tendency only in the salty taste that the proposed method shows an advantage over the previous method. This effect can be explained in the previous method when it is considered that the drink becomes resistant to electrical current flow through itself. Therefore, the current is lower than expected. In contrast, the proposed method is able to achieve the expected current through electrical stimulation directly to the tongue without the obstacle of the drink. We also evaluated the condition of addition by using t-test between the previous method and proposed method from Fig. 20. We determined whether there is a statistically significant difference for previous method-proposed method – t(4) = −3.162, p < 0.034. The significant difference was observed. Hence, it is considered that the proposed method can affect stronger salty perception to the tongue than the previous method. For the other flavors such as sweet, bitter, and sour, the difference between the two approaches in effect could not be observed by using the sports drink.

Through this experiment, we confirmed that the developed interface has the capability to affect a taste change continuously, however, we received a comment that the intensity of taste is decreased gradually. This response is regarded as the adaptation which is achieved by receiving a particular taste stimulation continuously, and then the sensitivity becomes lower gradually. Adaptation affects not only the electric stimulation but also normal foods and drinks [15]. In order to realize the taste change continuously, it is necessary to clear this problem in this.
5. Evaluation of Electrical Stimulation with Periodic Intervals

Nakamura and Miyashita [16] reported that the intensity of taste is increased after stopping the electrical stimulation using cathode. In the anode stimulation, it is known that the intensity of taste is not increased even if the electrical stimulation is stopped. However, we considered it is effective to prevent the adaptation.

Therefore, we evaluate the taste intensity when presenting anode stimulation intermittently. In order to represent this stimulation, we employ the method of electrical stimulation with periodic interval by using the PWM controls. It is necessary to determine the frequencies and the duty ratio for the PWM control. We prepare 3 kinds of frequency and 5 kinds of duty ratio and then perform the experiment to investigate which combination is effective for the adaptation.

5.1 Procedure

This experiment also uses a sports drink (produced by Otsuka Pharmaceutical Co. Ltd). We provided electrical stimulation with periodic intervals by using the developed intra-oral interface. The current is set as 1000µA. We perform the experiments using 16 patterns of electrical stimulation (Combination of 3 frequencies 1 Hz, 2 Hz, 5 Hz, and 5 duty ratios, 1:1, 2:1, 1:2, 4:1, 1:4) in addition to the direct current pattern. Figure 23 shows the PWM patterns when the duty ratio is changed. This pattern is randomly chosen when the subjects perform the evaluation. The period of the electrical stimulation is set as 5 s.

At first, we evaluate an effect of a constant electrical stimulation (i.e. 1000 µA is applied during 5 s) for each subject in order to compare the taste intensity for utilizing the periodic intervals. Next, subjects evaluate 16 patterns. Each subject evaluates the intensity of taste according to the six grade system [0: Not perceived at all, 1: Weakly perceived, 2: Slightly weakly perceived 3: Normally perceived 4: Slightly strongly perceived 5: Strongly perceived]. Finally, it is allowed to freely answer whether the intensity of taste has changed. This experiment is carried out with five subjects. All the subjects received explanations of the procedures and possible risks of the experiments and gave written informed consent to participate in the experiments.

5.2 Results and Discussions

Figure 24 shows the experimental results of the average value of the intensity of taste among each frequency and duty ratio. The vertical axis represents the intensity of taste, and the horizontal axis is duty ratio. The result of the taste intensity in the case of constant stimulation is scored 3 as shown in the horizontal line of Fig. 24.

When we compare with duty ratio, they are divided into a group of higher taste intensity (duty ratios are 1:1, 2:1, and 4:1) and a group of lower taste intensity (duty ratios are 1:2 and 1:4). As the reason for the group of lower taste intensity it is difficult to affect the intensity of taste because the interval becomes larger than the electrical stimulation period. The presenting electrical stimulation should be longer than half of the period, and then it affects the intensity of taste stronger than the constant stimulation.

One is that the intensity at 2 Hz is higher than those at the other frequencies for the duty ratios 1:1, 2:1, and 4:1. The other is that the intensity at 2 Hz is higher than that by the constant stimulation for the duty ratios 1:1, 2:1, and 4:1. This is because the period of electrical stimulation at the frequency of 1 Hz is too long and the taste intensity is lower than that at the frequency 2 Hz. The period of electrical stimulation at the frequency of 5 Hz is too short and the taste intensity is lower than that at the frequency 2 Hz. Thus, the combination of the duty ratio 2:1 and the frequency 2 Hz shows the highest score than the others in this experiment.

Finally, from the free answer when comparing constant electrical stimulation and electrical stimulation with periodic intervals, all subjects expressed the intensity of taste was decreased gradually in the case of constant electrical stimulation, even though it is not confirmed this effect in the case of electrical stimulation with the periodic interval. When the electrical stimulation is presented to tongue, the tongue adapts the stimulation within 5 s, and then the score of taste intensity becomes 3. On the other hand, because the electrical stimulation by PWM control works to avoid adaptation, it can sense electrical stimulation continuously during 5 s. As the result, it scored higher than constant case as shown in Fig. 25.
6. Conclusions

We measured the sensitivity related to the position and the area of the electrode which provided electrical stimulation to the tongue. The tip of the tongue was the highest sensitivity, and the sensitivity became lower so as to spread over lingual margin from there. In addition, the sensitivity of tongue was higher when the electrode area was smaller. From these knowledge, we developed the intra-oral interface to provide a change in taste continuously by using electrical stimulation. We performed experiments in order to clarify whether during drinking or not. From the experimental results, we confirmed that salty and metallic fulfilled the objective. The proposed method could affect stronger salty to the tongue than the previous method. Moreover, in order to prevent the adaptation, we proposed the approach of the electrical stimulation with periodic intervals by using PWM controls. Through the experiments, the combination of 2 Hz and duty ratio 2:1 is scored highest than the others including constant electrical stimulation. We confirmed the intensity of taste can be kept continuously by using periodic intervals. Thus, it is possible to affect the taste change continuously during drinking by using the intra-oral interface and electrical stimulation with periodic intervals.

In the future work, apart from the sports drink used in this paper, we will experiment this interface with other drink. We are planning to apply the proposed interface to diet and exercise rehabilitation of diabetes.

References


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