Chem. Senses 34: 325–331, 2009
doi:10.1093/chemse/bjp005
Advance Access publication February 16, 2009

Effects of Taste Solutions, Carbonation, and Cold Stimulus on the Power Frequency Content of Swallowing Submental Surface Electromyography

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Abstract

This study explored the effects of 5 taste solutions (citric acid, sucrose, sodium chloride, caffeine, and sodium glutamate) versus water on the power frequency content of swallowing submental surface electromyography (sEMG). Healthy subjects were presented with 5 ml of each of 5 tastants and water. Data were collected in 3 trials of the 5 tastants and water by using submental sEMG, which was then subjected to spectral analysis. Sour and salt taste solutions increased the spectrum-integrated values of the total power components. The spectrum-integrated values of low-frequency power (below 10 Hz) in the salt taste trial significantly increased, whereas those of high-frequency power (above 10 Hz) in the sour taste trial tended to increase. Neither pleasantness nor intensity of taste was related to these changes. This study also explored the effects of carbonation and cold stimulus on the power frequency content of continuous swallowing sEMG for 60-ml solutions. Carbonation significantly increased the spectrum-integrated value of the total power components by significantly increasing the high-frequency content. Cold stimulus significantly decreased the low-frequency content. In summary, this study reveals that taste, carbonation, and cold stimulus have qualitatively different influences on the power frequency content of swallowing sEMG.

Key words: electromyogram, frequency, pleasantness, salt, sour, spectral analysis

Introduction

Swallowing constitutes a complex sequential sensorimotor activity, which changes systematically or occurs randomly. Sensations from the oral, pharyngeal, and laryngeal regions encompass a broad range of modalities, including nociception and tactile, and thermal and chemical sensitivity (Miller 1982; Ali et al. 1994). This input is conveyed via trigeminal, glossopharyngeal, and vagus nerves, which innervate the muscles of the swallowing tract. Stimulation of any one of these nerves can modulate a swallow (Miller 1982).

Many recent studies indicate that swallowing is influenced by the nature of the ingested drink, which modulates activities of these nerves. Through the adaptation of biochemical and temporal measures, bolus properties such as temperature, volume, and texture are known to modulate swallowing behavior (Cook et al. 1989; Jacob et al. 1989; Bisch et al. 1994). The palatability and intensity of taste also have similar effects (Smith and Margolskee 2001).

There are 5 universally accepted tastes, sweet, salty, sour, umami, and bitter, and specific receptors for these tastes are found in oral, pharyngeal, and laryngeal regions. These basic tastes have been also shown to modulate swallowing. Chee et al. (2005) reported that sweet, sour, and salt tastes decreased swallowing speed as compared with water. In addition, the interswallow interval was increased by bitter and salt taste. Furthermore, Shingai et al. (1989) showed that neutral taste was the most effective stimulus for eliciting the swallowing reflex, as compared with sour, salt, and bitter tastes.

An electromyogram of muscle can provide information on the timing and relative amplitude of selected muscle contractions during swallowing. Using surface electromyography (sEMG), Ding et al. (2003) found stronger muscle contractions for salty boluses as compared with sweet and sour boluses. On the other hand, Leow et al. (2007) found that sour taste resulted in the greatest muscle contraction. Palmer et al. (2005) supported this finding by using intramuscular EMG to compare sour versus water swallows: they reported a stronger contraction of submental muscles for the sour taste bolus.

Although these reports on the influence of taste on the contraction of submental muscles vary due to the different

experimental conditions used, either sour or salt taste has been found to stimulate muscle contraction.

The aim of this study was to discriminate the qualitative differences in sEMG among different tastants. Some investigators have suggested that the power spectrum of EMG signals shifts in a predictable manner as a result of muscle fatigue (Palla and Ash 1981; Sadoyama and Miyano 1981; Hagg 1992; Lyons et al. 1993). Furthermore, it has been demonstrated that muscle fatigue shifts the mean power frequency to lower values (Dolan et al. 1995). We therefore hypothesized that taste stimuli would variously affect the power frequency content of swallowing submental sEMG.

In a clinical setting, a cold or sour bolus was found to facilitate triggering of the pharyngeal swallow in a dysphagic neurogenic subject (Logemann et al. 1995). Carbonated liquid has been reported to reduce penetration/aspiration into the airways, to reduce pharyngeal retention, and to decrease pharyngeal transit time (Bulow et al. 2003). By contrast, Ding et al. (2003) did not find any effects of carbonated water on the duration and activity of submental sEMG. Although Bisch et al. (1994) found that cold liquid caused significantly longer pharyngeal response times and longer laryngeal elevation in normal subjects, the effect of cold liquid on submental sEMG has not been reported. We therefore also examined the effect of carbonation and cold stimulus on the power frequency content of swallowing submental sEMG.

Materials and methods

Volunteers

Twenty volunteer subjects were recruited to take part in the study. Their mean age was 32.7 years, ranging from 26 to 45 years (9 males, 11 females). All subjects were free from medication and did not report any olfactory or gustatory disorders. Each subject reviewed and gave written informed consent to the protocol.

Taste stimuli

The taste stimuli were solutions of 102.7 g/l of granulated sugar (ION, Chiba, Japan; equivalent to 0.3 M sucrose) for sweet taste, 8.7 g/l of table salt (Shio Zaidan Center, Tokyo, Japan; equivalent to 0.15 M NaCl) for salt taste, 3.8 g/l of citric acid (Kanto Kagaku, Tokyo, Japan; equivalent to 0.02 M) for sour taste, 2.3 g/l of caffeine (Shiratori Yakuhin, Narashino, Japan; equivalent to 0.012 M) for bitter taste, and 12.6 g/l of sodium glutamate (Kirin Food Tech, Tokyo, Japan; equivalent to 0.067 M) for umami taste. Reverse osmotic water was used as the diluent and served as the control. All solutions were dispensed in a 5-ml volume and presented at room temperature (22–23 °C). The concentrations of sucrose, citric acid, and sodium chloride were determined as described in previous studies (Chee et al. 2005; Leow et al. 2007). The concentrations of caffeine and monosodium glutamate were determined to be the same perceived intensity as the sucrose, citric acid, and sodium chloride solutions, as described in previous studies (Mojet et al. 2003). A food additive grade of quinine HCl was not available; therefore, caffeine was used as the bitter taste.

For carbonated water, bottled seltzer water (Kirin Beverage, Tokyo, Japan) was used. Control water for carbonated stimulus was prepared by degassing the bottled seltzer water. For analysis of the effect of cold, Volvic water (Kirin MC Danone Waters, Tokyo, Japan) was chilled and used. Control water was prepared by keeping Volvic water at room temperature (22–23 °C).

Visual analog scales

For each of the 5 taste solutions, a visual analog scale (VAS) was presented to the subjects after one swallow of the solution. Subjects were asked to identify the taste and to rate its pleasantness or unpleasantness and its intensity. Participants rated pleasantness on a scale ranging from 0 (neutral) to 5 (extremely pleasant) or unpleasantness ranging from 0 (neutral) to –5 (extremely unpleasant). Intensity was rated on a scale of 0 (neutral) to 10 (extremely intense).

Surface electromyography

Surface electrode EMG was used. All EMG recordings for each participant were made by using standard surface electrodes (BLUE SENSOR, Ambu, Denmark). All electrodes were taped to the skin. The interelectrode distance between a pair of electrodes was about 10 mm. The specific electrode positions were as follows: a pair of bipolar surface electrodes was applied on the middle third of the right side of the lower and upper lips to record orbicularis oris activity, and a pair of bipolar surface electrodes was placed on the skin beneath the chin on the right side of midline to record submental activity. We used the sEMG trace of orbicularis oris as confirming of the start time of submental swallowing at the analysis of signal, because submental muscle always moves right later than the obicularis oris muscle. Muscle activities of the submental region include activities mostly from the anterior belly of the digastrics muscle, the mylohyoid muscle, and the geniohyoid muscle. The submental region was selected because these muscles are believed to be involved in both the oral and pharyngeal phases of a swallow (Dantas and Dodds 1990). A single grand electrode was affixed to the elbow.

The equipment used for the sEMG recording was a PERSONAL-EMG 4-channel computer-based EMG unit with Oisaka software (Oisaka Electronic Device, Hiroshima, Japan). The sampling speed was 3 kHz. The signals from 2 pairs of electrodes were amplified 1000 times. Analysis of the sEMG power spectrum was carried out by the maximum entropy method, using the MemCalc analyzer program (Suwa Trust, Sapporo, Japan). Spectral densities were calculated for the following frequency bands: 0.2–5, 5–10, 10–100, and 100–1500 Hz. We divided the power spectrum from 0.2 to 1500 Hz into various frequency bands and found that above fractionation reflected the most significant change. Spectral densities below 0.2 Hz could be negligible because they were too low to detect.

To estimate muscle activity, each EMG record was full-wave rectified, smoothed with a low-pass filter (cutoff frequency: 2.4 Hz), and amplified 4 times. The computer program indicated the mean and standard deviation of muscle activity during each trial, as well as its duration. Muscle activity (EMG) was quantified in millivolts.

Procedure (Experiment 1 [5 taste stimuli])

In this study, 14 subjects (mean age 31.6 years, 6 males, 8 females) were individually involved in a test session lasting 20 min. They were each requested to abstain from eating or drinking for 1 h. They were seated in a comfortable chair in a room at a constant temperature (23 °C). After 2 pairs of electrodes and the grand electrode were attached, subjects were verbally informed about the procedure. During the study, subjects were instructed to hold the stimulus material in their mouth for a few seconds before swallowing and to swallow the solution in a single swallow as they normally would.

Stimulus fluids were dispensed to participants as a 5-ml sample. Five taste solutions and control water were labeled at random with an alphabetical letter and presented in a randomized order. Subjects were instructed to rinse their mouth with Volvic water (Kirin MC Danone Waters) ad libitum after each solution. At the end of each swallow, the subject completed the taste VAS for pleasantness/unpleasant and intensity. Each solution was tested 3 times in a sequential, blind, randomized manner on 3 separate days. The duration of submental swallowing sEMG was defined as the onset of a rapidly increasing sEMG signal after the solution holding time until the return of the trace to the baseline surrounding the peak amplitude (Figure 1B). Power spectral analysis was applied to the raw signal (Figure 1A) of the corresponding submental swallowing sEMG (Figure 1C). The peak and mean amplitudes of the submental muscle contraction were also examined from the submental swallowing sEMG signals, which were full-wave rectified, smoothed, and amplified (Figure 1B).

Procedure (Experiment 2 [carbonated and cold stimuli])

In these studies, 12 subjects were separately recruited (for carbonated stimulus, mean age 32.3 years, males 5, females 7; for cold stimulus, mean age 33.8 years, males 4, females 8). All fluids presented to the subjects were between 11 and 14 °C except for the control sample (23 °C) in the cold stimulus test. Stimulus fluids were dispensed to participants as a 60-ml sample. Because carbonated water easily degasses and the temperature of cold water rapidly increases, the volume of stimulus was increased in this experiment. Subjects were equipped with sEMG probes as described above. Subjects were instructed to swallow the solution continuously in several swallows as they normally would. Carbonated and control water (or cold and control water) were alternately presented to the subjects at 2 different times on 2 separate days in a different order (total 4 times). The duration of first submental swallowing sEMG was defined as the onset of a rapidly increasing sEMG signal until the return of the trace to the baseline surrounding the peak amplitude after the last submental swallowing. Power spectral analysis was applied to the raw signal of the corresponding submental swallowing sEMG.

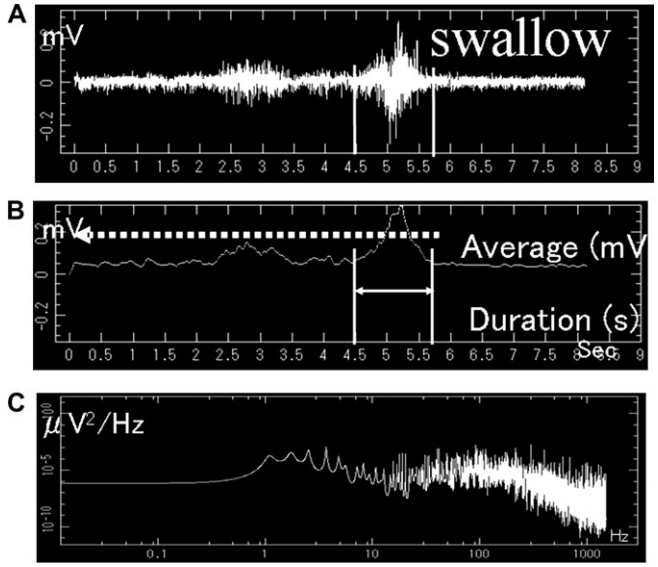

Figure 1 Example of the analysis of duration time, mean muscle activity, and power spectra of an sEMG signal for 5-ml swallowing. The raw sEMG signal **(A)** was rectified, smoothed, and amplified. **(B)** Power frequency analysis was applied to the corresponding raw sEMG signal (A), and the spectral density was obtained **(C)**. The duration of muscle activity was defined as the onset of the rapidly increasing peak amplitude until the return of the trace to the baseline surrounding the peak signal.

Data analysis

Results are expressed as mean values and standard error of 12 or 14 per group. In Experiment 1, the effect of taste solutions on the total power spectral densities, the spectral densities for each frequency band, and the peak, mean, and duration of the sEMG amplitude were tested by repeated-measures analysis of variance (ANOVA), using YSTAT2002 (Igakusyoten, Tokyo, Japan). Means between the sample and the control water were then compared using Dunnett's test. In Experiment 2, the spectral densities for each frequency band and the total power spectral densities were tested by a paired *t*-test. All differences were considered significant at a level of $P < 0.05$.

Results

Pleasantness/unpleasantness intensity rating

Figure 2A,B shows the means of the VAS ratings of pleasantness and unpleasantness on a scale of 0–5 for each taste modality and intensities on a scale of 0–10. The bitter solution was mostly perceived as an unpleasant stimulus, with a mean unpleasant score on the VAS of 2.67. Almost all subjects

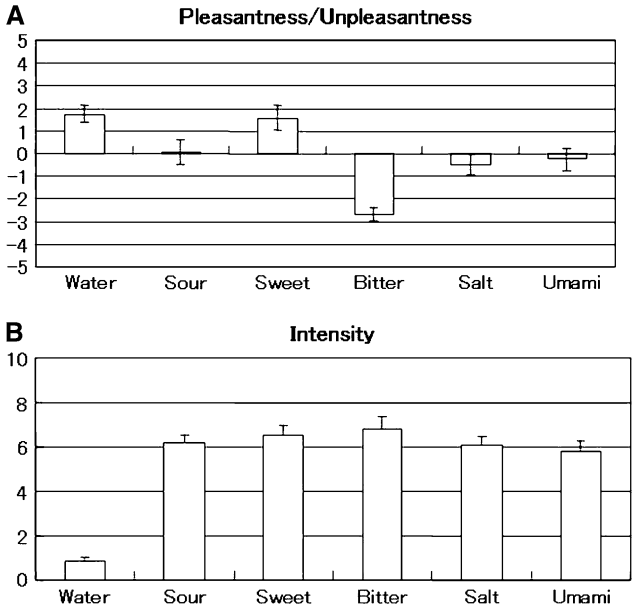

Figure 2 **(A)** Bar chart showing the group levels of pleasantness and unpleasantness to each different stimulus according to the VASs. **(B)** Bar chart showing the group intensity scores for each different stimulus according to the VASs.

(except for one) perceived the sweet solution as pleasant. The sour, salty, and umami solutions generated a mixed response with a pleasant score on the VAS of 0.07 and unpleasant scores on the VAS of 0.47 and 0.24, respectively.

The intensity ratings of each taste are shown in Figure 2B with the highest intensity for bitter, followed by sweet, sour, salt, and umami solutions. The control water evoked a mean intensity rating close to 0.

Power spectral analysis of submental swallowing sEMG

The mean total power spectral densities for the 5 taste and control solutions are shown in Figure 3A. Repeated-measures ANOVA revealed a significant effect of taste on the total power spectral density ($P < 0.01$, $F_{5,65} = 4.84$). Dunnett's test using water as the control showed that the sour and salt solution increased the total spectral density significantly ($P < 0.05$ and $P < 0.01$, respectively), whereas sweet, bitter, and umami had little effect on total power spectral density.

The spectral densities for the frequency bands of 0.2–5, 5–10, 10–100, and 100–1500 Hz are shown in Figure 3B,C,D,E, respectively. As with the total power spectral density, repeated-measures ANOVA yielded a significant interaction effect of taste on the 0.2–5 and 5–10 Hz densities ($P < 0.01$, $F_{5,65} = 6.90$; $P < 0.01$, $F_{5,65} = 15.15$). Furthermore, Dunnett's test using water as control showed that the salt solution significantly increased the 0.2–5 and 5–10 Hz densities ($P < 0.01$). Although there was no significant interaction effect of taste on the 10–100 Hz and 100–1500 Hz densities ($F_{5,65} = 2.18$ and $F_{5,65} = 2.43$, respectively), the sour solution tend to increase these 2 densities.

Mean amplitude and duration of sEMG

The mean amplitudes of sEMG are shown in Figure 4. As with the total power spectral density, repeated-measures ANOVA yielded a significant interaction effect of taste ($P < 0.01$, $F_{5,65} = 4.69$). Dunnett's test using water as the control showed that the sour and salt solutions significantly increased the mean amplitude ($P < 0.05$, $P < 0.01$, respectively). The changes observed were similar to those seen for the total power spectral density.

The durations of sEMG are shown in Figure 5. Repeated-measures ANOVA yielded a significant interaction effect of taste ($P < 0.05$, $F_{5,65} = 2.79$). Dunnett's test using water as the control showed that the sour and salt solutions significantly increased the mean amplitude ($P < 0.01$, $P < 0.05$, respectively).

Carbonated stimulus

The mean total power spectral densities for carbonated and control water are shown in Figure 6. A paired *t*-test revealed a significant effect of carbonation on the total power spectral density ($P < 0.05$). Spectral densities for each frequency band of 0.2–5, 5–10, 10–100, and 100–1500 Hz are shown in Figure 7. Carbonation significantly increased the 10–100 and 100–1500 Hz densities ($P < 0.05$ and $P < 0.01$).

Cold stimulus

The mean total power spectral densities for cold (11 °C) and control (23 °C) water are shown in Figure 8. A paired *t*-test did not reveal a significant effect of cold stimulus on the total power spectral density. The spectral densities for the frequency bands of 0.2–5, 5–10, 10–100, and 100–1500 Hz are shown in Figure 9. Cold significantly decreased the 0.2–5 Hz density ($P < 0.01$).

Discussion

The purpose of this study was to deduce the effects of taste, carbonation, and cold on the frequency content of swallowing submental sEMG.

We hypothesized that varying the taste stimulus would affect the frequency content of swallowing submental sEMG. Our results showed that sour and salt tastes cause an increase in the spectrum-integrated values of the total power components. Similarly, the mean sEMG amplitude tended to increase with these tastes. Previous research showed that either sour or salt taste was the strongest stimulant in terms of the value of the average sEMG amplitude (Ding et al. 2003; Palmer et al. 2005; Leow et al. 2007). Our results also showed that salt taste and sour taste are the strongest stimuli. Sour and salt tastes have been shown to evoke more afferent impulses (sensory input) to the solitary tract nucleus in the medulla oblongata in the brain stem (Logemann et al. 1995; Ding et al. 2003; Leow et al. 2007).

The VAS ratings of pleasantness/unpleasantness and the intensity of taste were also consistent with previous studies

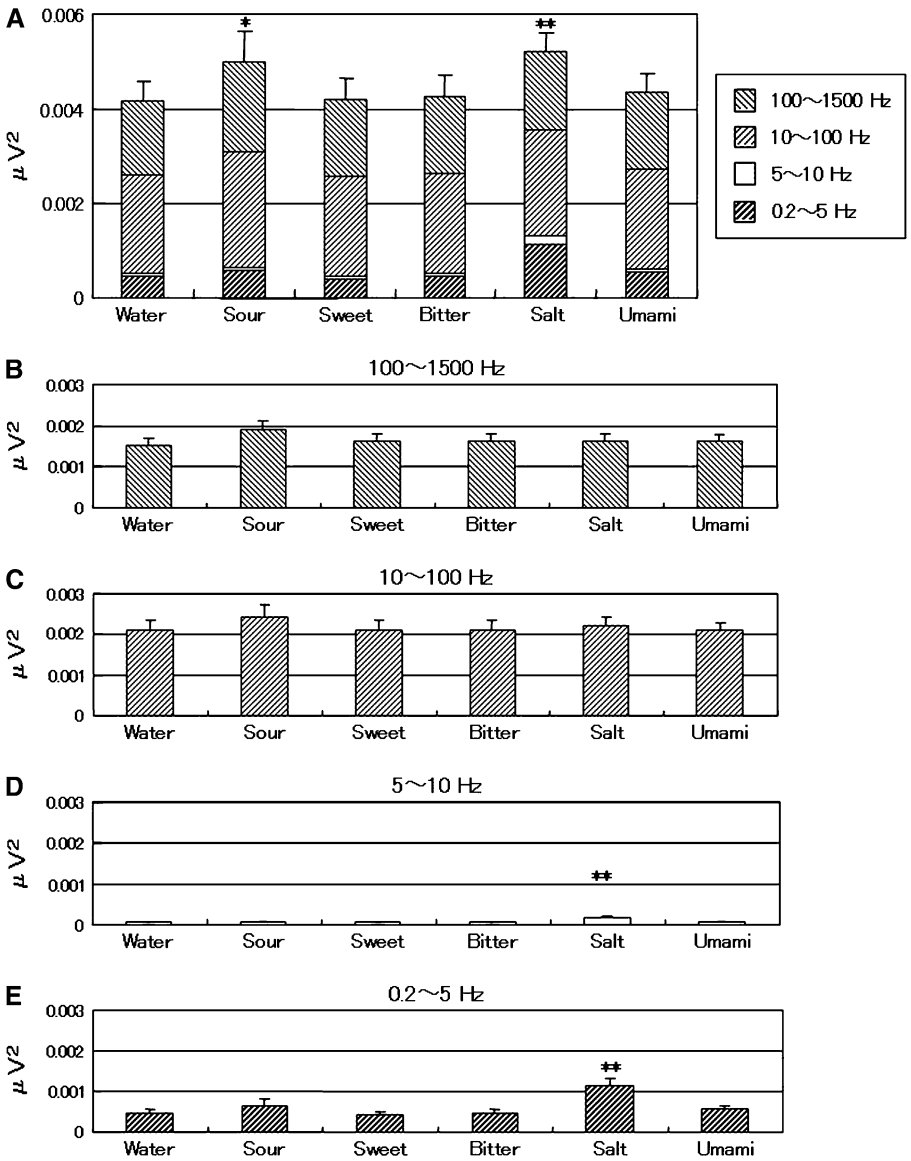

Figure 3 **(A)** Bar chart showing the total spectrum-integrated values of the total power components for each stimulus. As compared with water, the sour and salt solutions significantly increased the total power components (**$P < 0.01$, *$P < 0.05$, respectively). **(B)** Bar chart showing the frequency between 100 and 1500 Hz for each stimulus. Although there was no significant effect of taste on the frequency, the integrated value in the sour taste trial tended to increase compared with water. **(C)** Bar chart showing the frequency content between 10 and 100 Hz for each stimulus. Although there was no significant effect of taste on the frequency, the integrated value in the sour taste trial tended to increase compared with water. **(D)** Bar chart showing the frequency content between 5 and 10 Hz for each stimulus. As compared with water, the integrated value in the salt taste trial significantly increased. (**E**) Bar chart showing the frequency content between 0.2 and 5 Hz for each stimulus. As compared with water, the integrated value in the salt taste trial significantly increased (**$P < 0.01$, *$P < 0.05$, respectively).

in which the highest pleasant rating was obtained for sweet, followed by sour, umami, salt, and then bitter tastes (Chee et al. 2005; Leow et al. 2007). Thus, the stimuli used here could be judged to be very similar in taste intensity.

Neither the VAS rating of pleasantness/unpleasantness nor the VAS rating of intensity had any relationship with the changes in power frequency content. Therefore, the above observed changes were induced by chemical characteristics of the taste solutions.

We found that carbonation significantly increased the total spectral density. Ding et al. (2003) did not find any significant effect of carbonation on the amplitude or duration of submental sEMG. This difference in results stems from the experimental conditions. Because the volume of Ding's stimulus fluid was 5 ml, the carbon dioxide bubbles are likely to disappear very quickly before the participant is even ready to initiate the swallow; therefore, we examined the continuous swallowing of a 60-ml stimulus. The significant increase

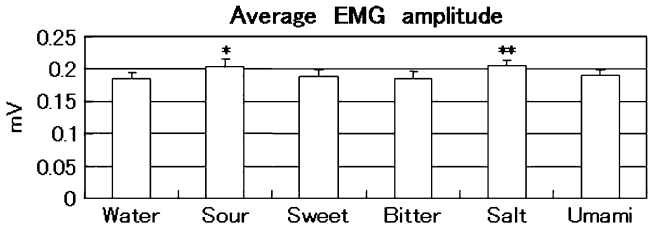

Figure 4 Bar chart showing the group average sEMG data for each stimulus. As compared with water, the sour and salt solutions significantly increased the mean amplitude (**P < 0.01, *P < 0.05, respectively)

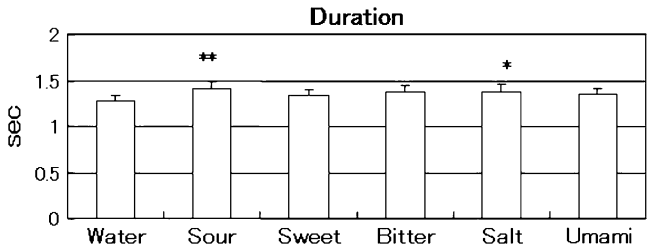

Figure 5 Bar chart showing the group average submental sEMG duration data for each stimulus. As compared with water, the sour and salt solutions significantly increased the mean amplitude (**P < 0.01, *P < 0.05, respectively).

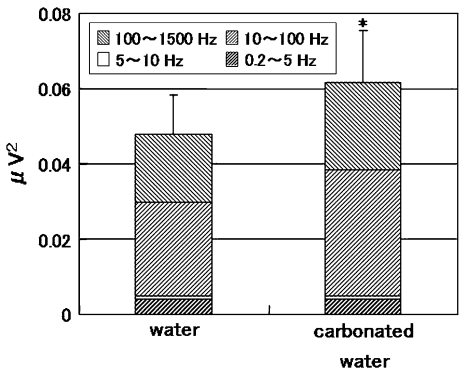

Figure 6 Bar chart showing the total spectrum-integrated values of the total power components for carbonated water. As compared with water, carbonated water significantly increased the total power components (*P < 0.05).

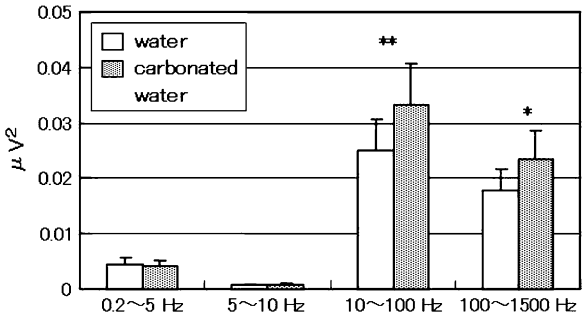

Figure 7 Bar chart showing the spectral densities for each frequency band of 0.2–5, 5–10, 10–100, and 100–1500 Hz for carbonated water. Carbonation significantly increased the 10–100 and 100–1500 Hz densities (**P < 0.01, *P < 0.05, respectively).

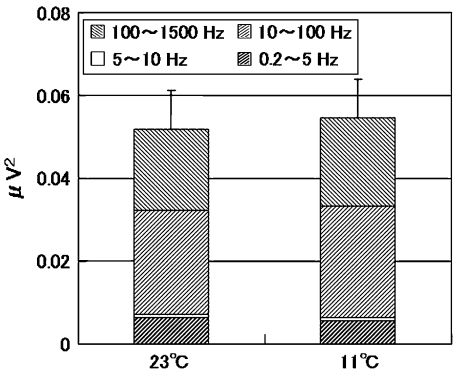

Figure 8 Bar chart showing the total spectrum-integrated values of the total power components for cold stimulus (11 °C). Although there was no significant effect of cold stimulus on the total power components, cooled water (23 °C) tended to increase the total power components.

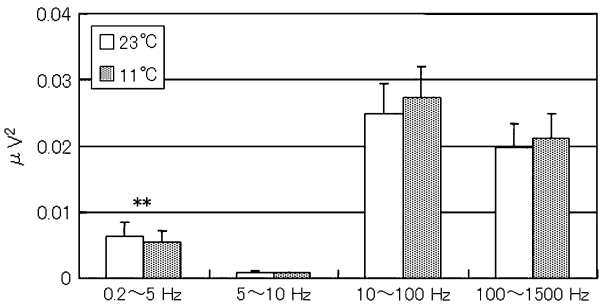

Figure 9 Bar chart showing the spectral densities for each frequency band of 0.2–5, 5–10, 10–100, and 100–1500 Hz for cold stimulus. Cold stimulus significantly decreased the 0.2–5 Hz densities (**P < 0.01).

in high-frequency densities is consistent with the effect of citric acid, for which the high-frequency densities tended to increase. Although a significant increase in the total spectrum-integrated value was not observed for the cold stimulus, a significant decrease in the 0.2–5 Hz density and a tendency toward an increase in the high-frequency content (>10 Hz) were observed.

Considering the above results, we propose a new general rule that swallow facilitators increase the high-frequency content (especially >100 Hz) and relatively decrease the low-frequency content (especially <5 Hz) of swallowing submental sEMG. It could also be said that swallow inhibitors increase the low-frequency content.

Although the physiological meaning of the frequency of sEMG is not yet clear, a decrease in medium frequencies has been observed during muscle fatigue (Palla and Ash 1981; Hagg 1992; Lyons et al. 1993). An increase in low-frequency content (below 30 Hz) has been reported to be

the most reliable index of fatigue (Dolan et al. 1995). Thus, muscle fatigue might be reflected into the low-frequency content (below 10 Hz). Indeed, in a study of the continuous swallowing of 60 ml of water in 4 sequential trials, symptoms of muscle fatigue were observed. The low-frequency content rate (below 10 Hz density/total spectrum-integrated density) increased significantly from 0.092 (1 and 2 time average) to 0.105 (3 and 4 time average) ($P < 0.01$, $n = 20$, data not shown).

Although it is uncertain whether swallowing a 5-ml taste solution induces perceived pharyngeal muscle fatigue, it could be said that a large volume of salt taste solution increases pharyngeal muscle fatigue more than the same volume of sour taste, carbonated, or cold stimulus solution. Sour taste, carbonated, and cold stimuli have been shown to facilitate swallowing in a clinical setting and may be consistent with activation of muscle contraction without muscle fatigue.

Logemann et al. (1995) hypothesized that a sour liquid bolus facilitates a more organized swallow by increasing the preswallow sensory input to the brain stem, thus allowing for more rapid approximation of the threshold required to trigger a swallow. Our results may confirm above hypothesis. The increase in low-frequency content observed during muscle fatigue was considered to be due mainly to an increase in the duration of the motor unit action potential, caused by a slowing of the conduction velocity of the action potential along the muscle fiber (Palla and Ash 1981). The increase in the high-frequency content of swallowing submental sEMG for the sour taste, carbonated, and cold stimuli is likely to reflect more organized activation of submental muscle, with more adequate and more effective afferent inputs into the solitary tract nucleus in the medulla oblongata in the brain stem. On the other hand, it could also be said that the salt taste bolus facilitates a nonorganized swallow, as reflected in the increase in the low-frequency content of swallowing submental sEMG.

Our data provide new insight into the role of oral chemosensory input in human swallowing physiology and offer a new simple method to evaluate the physiology of swallowing.

Acknowledgements

We thank Masako Shimura, Hiroko Mashima, and Makiko Neyazaki for valuable discussions.

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Accepted January 19, 2009