Effect of Carbon Dioxide in Carbonated Drinks on Linguapalatal Swallowing Pressure

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Abstract

This study aimed to investigate the influence of carbonated drinks with gas volumes (GV) of 0, 1.5, and 2.7 on linguapalatal swallowing pressure, intraoral carbonation perception, and maximum velocity of a bolus through the pharynx in healthy volunteers (N = 20, all female, age range; 20–21 years). The volunteers swallowed a 12-mL drink in the natural state. Linguapalatal swallowing pressure was measured using a special sensor sheet, and maximum velocity of the bolus through the pharynx was measured using ultrasonic diagnostic imaging equipment. Peak magnitude, integrated value, and duration of linguapalatal swallowing pressure and maximum velocity of a liquid bolus through the pharynx increased with an increase in carbon dioxide content in the carbonated drink. The total integrated values of carbonated drinks with GV of 1.5 and 2.7 were larger than that of the drink without carbon dioxide. These results suggest that the carbon dioxide dissolved in carbonated drinks influences the activity of taste receptors in the mouth and results in neuromotor responses.

Key words: air bubbles, carbonated drink, gas volume of carbonated drink, swallowing, tongue pressure, velocity through pharynx

Introduction

In the human body, the passage of a food or liquid bolus from the oral cavity through the pharynx is mediated by an organized series of motor events (Jean 1984). Among the muscle movements needed for swallowing, those of the tongue play an important role in the swallowing process. The tongue responds to chemical or physical stimulation, particularly the chemical stimulation caused by taste substances and pungent condiments (Green et al. 2005). Taste is recognized through stimulation of taste receptor cells by chemical substances dissolved in saliva or aqueous solutions (Gilbertson et al. 2000). These receptor cells are distributed throughout the oral epithelium and are innervated by the trigeminal and glossopharyngeal nerves. Several studies have found that a food bolus containing chemical substances that produce a sour taste influences swallowing physiology by causing greater neuromuscular recruitment (Logemann et al. 1995; Bulow et al. 2003; Chee et al. 2005). Sweet tasting substances activate the human sweet taste receptor (hT1R2-hT1R3), a heteromeric complex composed of T1R2 and T1R3 subunits (Nelson et al. 2001; Chandrashekar et al. 2006; Walters and Hellekant 2006; Winnig et al. 2007; Masuda et al. 2012), and their addition to beverages increases palatability and promotes the act of swallowing (Yamamura 2013). In addition, carbon dioxide in the form of carbonated water acts in the orosensory pathways by, for example, robustly stimulating the somatosensory system (Komai and Bryant 1993; Simons et al. 1999). Carbonated drinks are known to irritate oral mucosal nociceptors when the carbon dioxide dissolved in...
them reacts with the salivary enzyme carbonic anhydrase 4 to form carbonic acid (Simons et al. 1999; Dessirier et al. 2000), and the cellular and molecular substrates for the taste of carbonation are known (Chandrashekar et al. 2009).

The effects of carbonated drinks on swallowing in healthy adults and dysphagia patients has been studied by Ding et al. (2003) and Bulow et al. (2003). The latter group used videoradiography to assess swallowing of thin and thickened carbonated liquids in 40 dysphagic patients and found that, compared with thin carbonated liquids, thickened carbonated liquids reduced the penetration of materials into the airway. They recommended the use of thickened carbonated liquids for preventing aspiration in patients who aspirate thin carbonated liquids. The human tongue has a complicated neuromuscular architecture and produces muscular power in multiple directions. In response to intraoral perception, the tongue moves quickly, more quickly than other striated muscles (Slaughter et al. 2003; Bailey et al. 2007). Movement of a food bolus through the oral cavity is caused by positive pressure in a continuous longitudinal direction produced by the tongue contacting the hard palate (Gilbert et al. 2007). This characteristic movement has led several researchers to explore the relationship between linguapalatal swallowing pressures and differing task demands in healthy and disordered swallowing (Hiemae and Palmer 1999; Steele and van Lieshout 2005, 2008; Steele and Huckabee 2007; Steele et al. 2010; Felton et al. 2007). Various evaluation methods for linguapalatal swallowing pressure are available, but quantitative evaluation has proven difficult and is associated with many problems. One measurement method, developed by Ono, Hori and colleagues (Hori et al. 2009; Hirota et al. 2010; Konaka et al. 2010; Tamine et al. 2010), uses an ultra-thin pressure sensor sheet to measure linguapalatal swallowing pressure in 5 areas of the palate. Using the sensor, they found a constant swallowing pattern with defined values for tongue pressure, duration, and peak magnitude in healthy people while swallowing water. These values changed with age or swallowing difficulty.

The characteristic movement of a bolus through the pharynx is related to the physical properties of food. In our previous studies, we examined the swallowing characteristics and physical properties of agar gel in water, potato starch, guar gum, and xanthan gum (Sagawa et al. 2008). When agar gel was distributed in various thickening agents, it was clear that the physical properties of the bolus after mastication and the maximum transit velocity of the bolus are greatly influenced by the physical properties of the dispersion medium of the agar. Relationships between maximum transit gelatin have also been investigated: maximum transit velocity decreased with increasing concentrations of agar and gelatin (Moritaka and Nakazawa 2010).

In this study, we sought to investigate the influence of carbon dioxide content dissolved in carbonated drinks on linguapalatal swallowing pressure, maximum velocity of a bolus through the pharynx, and intraoral carbonation perception in healthy volunteers. We hypothesized that the increased orosensory input from the carbon dioxide content of a carbonated drink would provoke changes in swallowing reaction tasks compared with a noncarbonated drink. We also hypothesized that a higher content of carbon dioxide in a drink would alter linguapalatal swallowing pressure compared with a lower content of carbon dioxide.

Materials and methods

Sample

We dissolved fructose corn syrup, citric acid, and sodium citrate in distilled water, sterilized the solution for 40 s at 97 °C, then mixed it with pure water to produce 3 different carbonated drink samples with gas volumes (GV) of 0, 1.5, and 2.7 (hereinafter referred to as the GV0, GV1.5, and GV2.7 drinks, respectively). All 3 drink samples contained 11.0% fructose corn syrup, 0.12% citric acid, 0.04% sodium citrate, 8.0% sugar (pH 3.2, 0.12% acidity). We added fructose corn syrup to ensure that each carbonated drink could be swallowed as naturally as possible (Yamamura 2013).

Number and area of air bubbles

In the oral cavity, the physical stimulus of a carbonated drink is thought to change with the size and number of carbon dioxide bubbles, so we examined these parameters for each of the 3 drinks. We gently poured each drink from a height of 5 mm into a plastic laboratory dish (inside diameter: 82 mm; height: 10 mm). Images of the 3 drinks were acquired by video photography. Using Image J image processing software, the evaluators of the photographs, who were blinded to the GV in the drinks, evaluated the number, average area, and total area of air bubbles of the GV0, GV1.5, and GV2.7 drinks at the following time points (in seconds): 0, 15, 30, 45, 60, 90, 120, 150, 180, 240, 300, 450, 600, 750, 900, 1200, 1800, and 3000. Each measurement was repeated 5 times for each of the 3 drinks.

Apparent viscosity

Shi and Foster (2008) reported that viscosity of the saturated gas-expanded liquid system of carbon dioxide could be determined under pressure experimentally by using a falling weight viscometer. However, because the 3 drinks were swallowed under atmospheric pressure in this study, viscosity was measured using the conventional dynamic measurement method under atmospheric pressure. Although the measured value naturally cannot be used as an absolute value, it was considered to be an indicator of the physical characteristic of the drink with different carbon dioxide content. Because measured viscosity is not true viscosity, it is expressed as apparent viscosity, which was measured for each drink at 10 °C with a 10 s⁻¹ shear rate using MCR 300 (Anton Paar Co.) with cone plate geometry (50-mm diameter, 2° angle, 105 μm). We repeated the measurement 5 times for each of the 3 drinks. The measurement was started within 60 s after placing the sample on the sample stage.
Linguapalatal swallowing pressure

We recruited 20 female students aged 20–21 years from a university for women. The Institutional Review Board of Showa Women’s University (10-06) gave written approval for this study. The participants provided informed written consent. All subjects were healthy, free from neurological disease, had no history of head or neck surgery, recent or current oral lesions, or taste or swallowing impairments, and had no reason to avoid carbonated drinks. Constraints of the sensor sheet limited subjects in this study to those without wisdom teeth. The tactile sensor system, Swallow Scan (Nitta Co.) with a special sensor sheet for measuring linguapalatal swallowing pressure, was used according to Ono’s method (Figure 1) (Hori et al. 2006, 2010a, 2010b; Konaka et al. 2010; Ono et al. 2004, 2009; Tamine et al. 2010). This sensor sheet, composed of 0.05-mm resin, has 5 measuring points. We directly attached a small, medium, or large sensor sheet, as appropriate to the subject, to the palatal surface of the palatal mucosa with a sheet-type denture adhesive (Touch Correct; Shionogi). Three measuring points, Chs. 1–3, were placed along the median line: Ch. 1 was positioned on the anterior median area, Ch. 2 on the mid-median area, and Ch. 3 on the posterior median area. Two sensors (Chs. 4 and 5) were situated on the posterior circumferential parts of the hard palate. Subjects were instructed to sit in a chair with their head in the Frankfort plane, parallel to the floor. According to the results of an exploratory experiment in which it was found that a 12-mL sample is needed to swallow a drink in the natural state, subjects drank a 12-mL sample, which usually swallowed within 1 or 2 swallows. We used stable data from the first swallow for analysis. We analyzed waveforms for times of onset, peak, duration, peak magnitude (maximum pressure of the tongue pushing on the hard palate), and integrated values of linguapalatal swallowing pressure (Figure 2). Figure 3 shows the representative waves of linguapalatal swallowing pressure acquired at Ch. 1. The integration value was calculated from the area under the linguapalatal swallowing pressure curve. The 3 drinks were measured in random order.

Bolus velocity through the pharynx

The same 12 subjects were instructed to sit up straight and deeply in a chair. We then measured the maximum velocity of the GV0, GV1.5, and GV2.7 drinks moving through the pharynx by the pulse Doppler method using ultrasonic diagnostic...
imaging equipment (NEM10 SSA-550A; Toshiba Medical Systems). Measurement was carried out at an ultrasonic frequency of 6.0 MHz, a pulse frequency of 10.4 kHz, and 80% brightness using a scanning probe (PLM-703AT; Toshiba Medical Systems). According to the method of Moritaka and colleagues (Moritaka and Nakazawa 2009, 2010; Sagawa and Moritaka 2012; Inoue et al. 2009) and Nakazawa et al. (2000), we affixed the scanning probe to the central part of the pharynx at a 60° angle relative to the horizontal. Subjects swallowed a 12-mL sample of each of the drinks in the natural state. For each subject, we repeated the measurement 30 times for the same 3 drinks to obtain a tongue pressure measurement.

Sensory evaluation

The same subjects also completed a sensory evaluation of each of the 3 12-mL drink samples. We tested each sample 5 times on different days in a room with the temperature set at 25 °C. Subjects used a 7-point scale to rate each randomly allocated sample for the following items: “stinging sensation in the mouth” (−3: very weak, −2: weak, −1: a little weak, 0: neither, +1: a little strong, +2: strong, +3: very strong), “strength of swallowing” (−3: very difficult, −2: difficult, −1: a little difficult, 0: neither, +1: a little easy, +2: easy, +3: very easy), “strength of swallowing after swallowing” (−3: very weak, −2: weak, −1: a little weak, 0: neither, +1: a little strong, +2: strong, +3: very strong), “stinging sensation after swallowing” (−3: very weak, −2: weak, −1: a little weak, 0: neither, +1: a little strong, +2: strong, +3: very strong), and “preference” (−3: very weak, −2: weak, −1: a little weak, 0: neither, +1: a little strong, +2: strong, +3: very strong). For strength of swallowing, we asked the subjects to evaluate the extent of extra power needed to swallow the drink.

Statistical analysis

All research data sets were anonymized. Statistical analyses were performed using SPSS 17 (SPSS Inc.). Homoscedasticity of variance was verified with Levene’s test in relation to onset time, peak time, duration, peak magnitude, integrated value, and total integrated value of linguapalatal swallowing pressure, maximum velocity of the bolus through the pharynx, and the rating scores of each of the sensory evaluation parameters. As a result, all data sets were analyzed by the nonparametric Kruskal–Wallis test with Bonferroni’s correction. Number and area of air bubbles were verified by Levene’s test and were then compared using repeated measures ANOVA followed by Tukey’s test at the same measured times. P values less than 0.05 were taken to indicate statistical significance, and values are expressed as means (± standard error).

Results

Number and area of air bubbles

Figure 4 shows the number of bubbles per cm², average area per bubble, and total area per cm² of the GV0, GV1.5, and GV2.7 drinks. The number of bubbles per cm² for the GV2.7 drink rapidly decreased after being poured into the laboratory dish and was stable from 450 to 3000 s. The bubbles in the GV1.5 and GV2.7 drinks showed repeated disappearance and formation. The number of bubbles in the GV1.5 drink was low immediately after being poured into the laboratory dish, and after reaching a maximum, decreased to a number comparable to that of the GV2.7 drink at around 120 s. The average area per bubble just after being poured was larger for the GV2.7 drink than for the GV1.5 drink; it then increased slowly and reached a maximum at 600–750 s. The average area per bubble for the GV2.7 drink decreased at 750 s and onward, and then became comparable to that of the GV1.5 drink. Although the average area per bubble in the GV1.5 drink was small immediately after being poured, it increased until 300–450 s and then became comparable to that of the GV2.7 drink. The total area of carbon dioxide bubbles per cm² tended to be larger for the GV2.7 drink than for the GV1.5 drink. However, the total area of carbon dioxide bubbles per cm² of the GV2.7 drink became comparable to that of the GV1.5 drink after 1200 s.

Apparent viscosity

Figure 5 shows the representative apparent viscosity of the GV0, GV1.5, and GV2.7 drinks. The apparent viscosity of the GV0 drink was 1.8 mPa·s. The apparent viscosity of the GV1.5 and GV2.7 drinks decreased over time. Although apparent viscosity was higher in the GV2.7 drink than in the other drinks at the start of measurement, it became comparable to that of the GV1.5 drink. When the GV1.5 and GV2.7 drinks were vigorously stirred with a glass stick, the apparent viscosity of these drinks became the same as that of the GV0 drink.

Linguapalatal swallowing pressure

Onset time and peak time

Figure 6a shows the onset time of peak linguapalatal swallowing pressure for the GV0, GV1.5, and GV2.7 drinks. The
onset time of peak linguapalatal swallowing pressure peak at Ch. 1 for each task was set to 0 s. For all 3 drinks, onset time in the anterior median area (Ch. 1) appeared earlier than that in the posterior median area (Ch. 3) and posterior circumferential areas (Chs. 4 and 5) (Figure 6a). We observed no significant differences in onset time or peak time among the 3 drinks in any channel (Figure 6b).

**Duration**

For each of the 3 drinks, duration of linguapalatal swallowing pressure at the posterior median area (Ch. 3) was shorter than that of all other hard palate areas (Chs. 1, 2, 4, and 5) (Figure 6c). The duration at the anterior median and the mid-median areas (Chs. 1 and 2) of GV0 and GV2.7 were longer than those at the posterior circumferential areas (Chs. 4 and 5). At all channels (Chs. 1–5), linguapalatal swallowing pressure was significantly shorter for the GV0 drink than for the GV1.5 and GV2.7 drinks except at the mid-median area (Ch. 2), but there was no significant difference between the GV1.5 and GV2.7 drinks.

**Peak magnitude**

At all hard palate areas (Chs. 1–5), peak magnitude was significantly smaller with the GV0 drink than with the GV2.7 drink (Figure 6d). At the posterior circumferential areas (Chs. 4 and 5), peak magnitude of the GV1.5 drink was larger than that of the GV0 drink. However, we observed no significant differences between the GV1.5 and GV2.7 drinks at any channel. We observed no significant differences at any of the channels for any of the 3 drinks.

**Integrated value of peak swallowing pressure**

In each drink, the integrated value of peak linguapalatal swallowing pressure was larger at the anterior median area (Ch. 1) and mid-median area (Ch. 2) than at the other channels (Chs. 3–5) (Figure 6e). At all channels (Chs. 1–5), the integrated value of the GV0 drink was smaller than that of the GV1.5 and GV2.7 drinks. At the mid-median area (Ch. 2) and 1 posterior circumferential area (Ch. 4), the integrated value was smallest for the GV0 drink, followed by the GV1.5 and then the GV2.7 drinks.

**Total integrated value of all channels**

The total integrated value of the GV0 drink was smaller than that of the GV1.5 and GV2.7 drinks (Figure 6f). However, there was no significant difference in total integrated value between the GV1.5 and GV2.7 drinks.

**Transit velocity through the pharynx**

The maximum transit velocity through the pharynx of the GV2.7 drink was faster than that of the GV0 drink (Figure 7). However, there was no significant difference in maximum transit velocity between the GV1.5 and GV2.7 drinks.

**Sensory evaluation**

Figure 8 shows the sensory evaluation results. We found no significant difference in “preference” among the drinks, but found a significant difference in “strength of swallowing” between the GV0 drink and the GV1.5 and GV2.7 drinks. For “stinging sensation in the mouth,” “ease of swallowing,” and “stinging sensation after swallowing,” we observed significant differences between the GV1.5 and GV2.7 drinks.

**Discussion**

Previous studies on linguapalatal swallowing pressure have used commercial carbonated drinks as samples. However, the various ingredients and carbon dioxide contents of commercial carbonated drinks have confused the relationship between carbon dioxide content and linguapalatal swallowing pressure. In this study, the drink samples contained exactly the same ingredients with the exception of carbon dioxide in order to keep constant the apparent viscosity of the noncarbonated drink. We also prevented changes in carbon dioxide content by opening the carbonated drink containers immediately before measurement. Furthermore, we used ultra-thin sensor sheets with 5 pressure-sensitive points in order to measure swallowing pressure in the natural state.

We found that contact between the tongue and anterior median area of the hard palate started earlier than that at the posterior median and posterior circumferential areas (Figure 6a). For the GV0 and GV2.7 drinks, duration of linguapalatal swallowing pressure was longest at the anterior median and mid-median areas (Chs. 1 and 2), followed by the posterior circumferential areas (Chs. 4 and 5), with the posterior median area (Ch. 3) being the shortest (Figure 6c).
Ono et al. (2004) measured linguapalatal swallowing pressure when swallowing 15 mL of water. They found that contact time was longest in the anterior median area, followed by the mid-median and posterior circumferential areas. Kennedy et al. (2010) reported that contact between the tongue and anterior hard palate was variable and longer than that with the posterior hard palate when swallowing 10 mL of water. These findings together with those of the present study indicate the contact pattern between the tongue and hard palate when swallowing carbonated drinks is similar to that when swallowing water.

However, we observed for all areas of the hard palate that 1) duration, maximal magnitude, and integrated value of linguapalatal swallowing pressure was affected by the carbon dioxide content of the drink (Figure 6c–e); 2) the duration of linguapalatal swallowing pressure with the noncarbonated GV0 drink was significantly shorter than that with the carbonated GV1.5 and GV2.7 drinks (Figure 6c); and 3) peak magnitude of linguapalatal swallowing pressure with the noncarbonated GV0 drink was significantly smaller than that with the carbonated GV2.7 drink (Figure 6d). Furthermore, the integrated value of linguapalatal swallowing pressure...
carbonic anhydrase 4 to form $\text{H}_2\text{CO}_3$ (Dessirier et al. 2000). When the $\text{H}_2\text{CO}_3$ separates into bicarbonate ions and free protons in the oral cavity, protons stimulate sour-sensitive taste receptor cells innervated by the facial nerve, yielding a perception of sourness:

$$\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+$$

Moreover, Wang et al. (2010) showed that carbon dioxide specifically activates a subpopulation of trigeminal neurons that express TRPA1. Therefore, the influence of different carbon dioxide content on perceptive input is considered a possible reason behind the present results.

The content of carbon dioxide differed considerably between the GV1.5 and GV2.7 carbonated drink samples examined in this study. However, we found no clear difference between the carbonated GV1.5 and GV2.7 drinks. We consider the cause to be as follows. The difference in acidity by carbon dioxide dissolved in the carbonated GV1.5 and GV2.7 drinks might have diminished with the addition of citric acid and sodium citrate. Furthermore, because acidity is suppressed by sweet taste, corn syrup might have inhibited the stimulation by carbon dioxide (Takahashi and Nishinari 2010). Komai and Bryant (1993) and Simons et al. (2007) revealed that carbon dioxide acts in the orosensory pathways and robustly stimulates the somatosensory system. The total area of carbon dioxide bubbles per cm$^2$ in the GV2.7 drink tended to be larger than that in the GV1.5 drink (Figure 4c). The apparent viscosity of the GV2.7 drink was larger than that of the GV1.5 drink in the early stage of measurement (Figure 5). However, in regard to the sensory evaluation of stinging sensation in the mouth and stinging sensation after swallowing, we observed no significant difference between the carbonated GV1.5 and GV2.7 drinks (Figure 8a,d). These results suggest that the physical stimulation caused by carbon dioxide bubbles in the oral cavity might produce little receptor activity and neuromotor response.

The characteristic movement of a bolus through the pharynx is related to the physical properties of food (Nakazawa et al. 2000; Hasegawa et al. 2005, 2008; Sagawa et al. 2008; Tashiro et al. 2010; Moritaka and Nakazawa, 2009, 2010; Moritaka et al. 2012). The pharyngeal bolus transit velocity of xanthan gum and guar gum sols decreased with increasing the apparent viscosity (Sagawa and Moritaka 2012). We found that the carbonated GV2.7 drink moved significantly faster through the pharyngeal region than the noncarbonated GV0 drink. The flow of carbonated drinks was hampered by the presence of carbon dioxide bubbles. These bubbles underwent repeated disappearance and generation over time and then decreased. As measuring time became longer, the apparent viscosity of the GV 2.7 and GV 1.5 drinks decreased (Figure 5) and when they were vigorously stirred with a glass stick, their apparent viscosity became the same as that of the noncarbonated GV0 drink. When strong positive pressure acts on a carbonated drink in the oral cavity, the disappearance of air bubbles is promoted and
the number of bubbles disturbing the flow of the carbonated drink decreases. We assume that the carbonated GV2.7 drink passed more quickly through the pharyngeal region than the noncarbonated GV0 drink due to a decrease in the number of bubbles as a result of strong positive tongue pressure and strong forceful movement through the pharynx.

The results of this study clearly show that stimulation by carbon dioxide can affect tongue movement, which produces the power needed to move a drink bolus through the oral cavity, and that a high concentration of carbon dioxide causes greater impact between the hard palate and tongue than occurs with a low concentration. These findings provide clinically valuable basic data on the effect of a stimulant in the oral stage of swallowing. Future research on this topic should include elderly people since swallowing patterns alter with age.

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**Conflict of Interest statement**

S.S., T.T., and I.A. are employed by ITO EN LTD.

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**Figure 8**

Distance scale of the sensory evaluation of carbonated drink with different GV. (a) Stinging sensation in the mouth (GV0 < GV1.5, 2.7 [*P < 0.05*]), (b) ease of swallowing (GV0 > GV1.5, 2.7 [*P < 0.05*]), (c) strength of swallowing (GV0 < GV1.5, 2.7 [*P < 0.05*]), (d) stinging sensation after swallowing (GV0 < GV1.5, 2.7 [*P < 0.05*]), (e) preference.


