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Simultaneous Real-Time Measurements of Mastication, Swallowing, Nasal Airflow, and Aroma Release

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Mastication, swallowing, breath flow, and aroma release were measured simultaneously in vivo using electromyography, electroglottography, a turbine air flow meter, and the MS-Nose, respectively. Signals were synchronized either electronically or by aligning the nasal airflow data with the breath by breath release of acetone. Chewing affected nasal airflow, with the flow fluctuations following the mastication pattern. Data analysis suggested that air was pumped out of the mouth into the throat with each chew, and the mean volume was 26 mL. Aroma release was associated with the pulses of air pumped from the mouth with each chew. During swallowing, there was no nasal airflow, but after swallowing, aroma release was evident. The volume of the retronasal route was estimated at 48 mL when swallowing and 72 mL when samples were chewed. The combination of techniques shows the effects of physiological processes on aroma release.

KEYWORDS: EMG; EGG; Laryngograph; nasal airflow; API-MS; MS-Nose

INTRODUCTION

The overall perceived flavor of a food relies heavily on the way the volatile aroma compounds are released in mouth and transported to the olfactory receptors in nose as the food is consumed. In-mouth, physiological processes such as mastication (*1*−*3*) play a key role in releasing aroma compounds from the food matrix, while processes such as swallowing (*4*, *5*) and nasal airflow (*1*) determine their subsequent delivery to the olfactory receptors in the nose. However, the exact role and relative importance of each physiological action on the aroma release and transport is unclear. The current understanding is that mastication breaks down and hydrates food with saliva (where appropriate) until it is in a suitable form for swallowing. There is some evidence that the chewing action of the jaw pumps flavor-enriched air from the mouth into the tidal breath stream (*1*). This assumes that the barrier between the mouth and pharynx (formed by the soft palate and the base of the tongue) is open (or opens regularly), allowing air to move between the two regions, a principle used in the design of model mouth systems, designed to simulate volatile release during mastication (*6*, *7*). Buettner (*5*) studied the processes involved in swallowing solutions of ethyl butyrate using videofluoroscopy and real-time magnetic resonance imaging. She demonstrated that the barrier between the mouth and the pharynx opened intermittently and suggested that retronasal pulses of aroma, delivered to the nasal receptors during mastication, originated from the swallowing of small portions of solution. In other experiments, it was shown that helium gas could be held in the mouth and totally sealed from the throat (*4*). Although the veracity of these experiments is not in doubt, it is still not clear exactly when (and under what conditions) the pharynx is open and aroma transport from mouth to nose occurs. Results from research on swallowing disorders suggest that the respiration and swallowing processes are highly coordinated, ensuring that there is no air movement throughout the pharyngeal stage of swallowing (stage of bolus transfer) (*5*, *8*−*10*). This avoids aspiration of food into the airways or lungs but also means that there is *no* transfer from the mouth to the nose during swallowing; it can only take place *after* swallowing, when air is expired from the lungs (*5*).

To make further progress in this area, it is necessary to develop methods so that mastication, swallowing, nasal airflow, and aroma release can be monitored simultaneously. Mastication is conveniently followed by ElectroMyoGraphy, EMG (*2*, *11*−*13*), while nasal air flow can be monitored using appropriate turbine flow devices (*14*). Swallowing has been monitored using a swallow button, in which the panelist presses a button when they have swallowed (*13*). As swallowing actions are rapid events, this technique is only capable of giving a rough indication of when a swallow occurred. For more accurate timing of the swallow, other techniques have to be employed that directly monitor physiological movements associated with the swallowing action. Videofluoroscopy (*5*) requires a special working environment, which prohibits the collecting of other types of physiological or aroma release data. An alternative is the Laryngograph, designed for use in speech therapy but used here for swallowing measurements. The technique monitors laryngeal behavior, and one of the main responses is vocal fold closure during the pharyngeal stage of swallowing (*15*, *16*). During the normal respiration cycle, the vocal folds are apart (adopting a V shape configuration, if looked at from above)

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(*8*), allowing air to move through the trachea and into the upper airways. Once the reflexive swallow has been initiated, they come together to close off the trachea from the upper airways, with the aim of preventing food/liquid from entering the lungs (*8*). Monitoring real-time release of aroma compounds in the breath using on-line mass spectrometric methods (*17*) is well documented. Given the relatively short times involved (the breathing cycle is around 3 to 5 s), one of the key issues is to ensure that the separate data streams are perfectly aligned on the time axis so that the relationships between the physiology and aroma release processes can be clearly recognized.

MATERIALS AND METHODS

Breath Volatile Measurement. The volatile compounds present in expired air from the nose were measured with an atmospheric pressure chemical ionization-mass spectrometer (APCI-MS; MS-Nose, Micromass, Manchester, UK). Samples of the breath were drawn at 35 mL/min into the ionization source through a heated (160 °C) deactivated fused silica tubing (1 m × 0.53 mm i.d.) to prevent condensation of the volatile compounds. Compounds entering the source were ionized by a 4kV positive ion corona pin discharge, and the ions formed were introduced into the high vacuum region of the mass spectrometer, where they were separated and detected according to their *m*/*z* ratio as described previously (*17*). The volatiles studied were detected at masses corresponding to their protonated molecular ion (MH^+).

Breath Flow Rate Measurement. The rate and volume of the nasal airflow was monitored using a digital volume transducer (World Precision Instruments, Stevenage, UK), suitable for flow rates up to 3 L/sec. It consists of an optoelectronic pick-up assembly contained within a small cartridge. The cartridge was placed in line with the breath flow. The air movement associated with inhalations and exhalations caused an ultra lightweight impeller blade to spin in one direction for exhalations and the opposite for inhalations. As the impeller rotated, it sequentially interrupted light beams generated by light emitting diodes, and these interruptions were detected by photo transistors. These signals were input into a 1401 Mk II (Cambridge Electronic Design (CED), Cambridge, UK) analogue to digital converter (ADC) and then processed using a computer software package (Spike 2 from CED) specifically designed to handle physiological data.

Mastication Measurements (Electromyography, EMG). The process of mastication was followed by detecting the activity associated with the contraction of the masseter muscle, described previously by Brown (*11*, *12*) and Sprunt (*13*). This muscle was located by palpation and was found down the side of the jaw. The activity of this muscle was determined by placing bipolar surface electrodes (Medicotest UK Ltd) at either end of the muscle, approximately 1 cm apart. An additional electrode, acting as a ground, was placed on the shoulder blade. The raw signal was fed into a 1902 signal conditioner (CED), which filtered out low-frequency noise. The filtered signal was then input into the 1401 Mk II and converted to a 5 kHz digital signal. Finally, the data was collected and analyzed using the computer software package, Spike 2 (CED).

Swallowing Measurements. Electroglottography (EGG) was used to monitor the pharyngeal stage of swallowing. A laryngograph (Laryngograph LTD, London, UK) measured the electrical impedance across the throat during the eating process. An AC sinusoidal current of alternating frequency, typically between 300 kHz and 5 MHz, was passed between two circular electrodes, 2 cm in diameter, that were made of copper. Each of the two copper electrodes had an additional ring electrode encircling each of them, which acted as a reference for impedance measurements, increasing the overall diameter of each electrode to 3 cm. They were attached to a flexible, adjustable band held in place around the throat at the level of the thyroid cartilage and positioned approximately 3 cm apart. The sensing electrode detected the current as it passed through the skin and throat. The amplitude of the signal relates to the degree of tissue impedance in the current's path. Tissue impedance is lower than air impedance, therefore as the vocal folds closed (initiated by the reflexive swallow), the current passing through the larynx increased. The activity of the vocal folds was monitored and used to determine the pharyngeal stage of swallowing. The signal was input directly into the 1401 Mk II, where it was converted to an 800 Hz digital signal. The Spike 2 computer software package was used to process and analyze the data.

Samples. To ensure regular mastication, five panelists selected from within the food sciences division placed a piece of unaromatized chewing gum (Firmenich SA, Geneva) in mouth and were instructed to chew four times during each exhalation (and not to chew on inhalation) to determine the influence of mastication on nasal airflow. This eating protocol was used because it simplified the EMG traces; each set of 4 peaks, which corresponded to the chew events, were clearly separated from each other, simplifying the data analysis. Solutions of ethyl butyrate (100 ppm; Firmenich SA), were then pumped (Harvard Apparatus, USA), through a length (30 cm) of 1/8 in. PFA (perfluoroalkoxy) thermoplastic tubing (Swagelok, Ohio, USA) at 5 mL/min for approximately 1 min into the side of panelists' mouths. The panelists were instructed not to swallow throughout this time period. The panelists were given time to practice the eating protocols and to familiarize themselves with the equipment. The aroma release profile, EMG, and nasal airflow trace were measured (eight replicates for each panelist over two exhalations) to determine the influence of mastication on aroma delivery. A similar experiment was carried out, in which panelists were instructed to breath normally into the turbine, while avoiding any significant mouth movements. This allowed us to compare nasal airflows during normal breathing with airflows while a piece of gum was masticated. In a separate experiment, panelists (five) were instructed to suck a portion (for approximately 2 s) of an orange drink (Robinsons, Chelmsford, UK) through a straw and then swallow the liquid. The volatile profile, EGG, and nasal airflow were monitored over time (30 s) to determine the effect of swallowing on aroma delivery.

RESULTS AND DISCUSSION

Alignment of Physiological Response Signals with Aroma Release Profiles. The comparison of the physiological responses (EMG, EGG, and nasal airflow) and aroma release (in vivo measurements with APCI-MS) was only possible if the two independent data streams were aligned accurately. The temporal alignment of the three physiological responses (EMG, EGG, and nasal airflow) was straightforward, as all the signals were input directly into the same analogue to digital converter (1401 Mk II), resulting in as near to perfect synchronization as is possible with modern day electronics. Combining the APCI-MS data with the human physiology data was more complex, as it involved synchronizing two independent streams of data.

For breath aroma release studies in vivo, the APCI-MS is usually set to monitor acetone, a compound that is naturally present in breath and that can be used as a marker for exhalation. Inhalations and exhalations were also monitored using the flow sensing turbine, in which a positive flow represented an exhalation and a negative flow an inhalation. It was therefore possible to synchronize the two data streams using the acetone trace and the nasal airflow trace (**Figure 1** shows a typical pair of traces). The traces were aligned using the start of an exhalation, which was defined as the moment a positive flow rate was recorded using the turbine, and acetone was detected with the APCI-MS (marked **1** in **Figure 1**). The end of the exhalation was the time at which the flow rate reversed (i.e., became negative) and the acetone concentration began to fall (marked **2** in **Figure 1**). The falling concentration of acetone detected by the APCI-MS after this time point corresponded to the clearing of the turbine mounting of all traces of acetone. In all cases, if the traces were aligned using the "start" criteria, the end of the exhalation was aligned within 0.1 s. The method was therefore deemed to be reliable and appropriate. Once the two data sets were aligned, the influence of each physiological response on the aroma release profile was studied. This

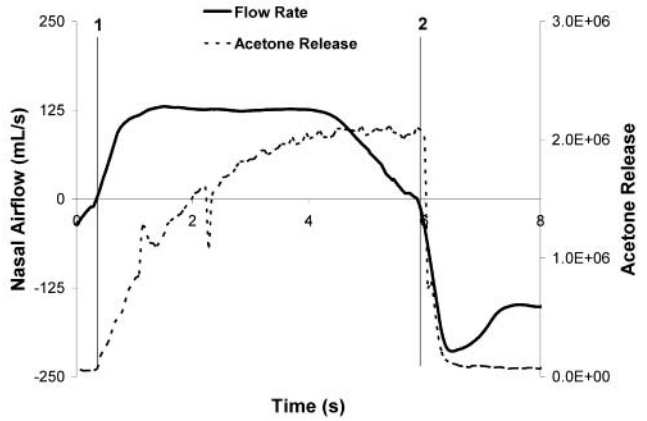

Figure 1. The relationship between the nasal airflow and acetone profile. The graph shows the two traces aligned using the start point (1). The end of an exhalation is also marked (2). The variation in fitting was determined by the time between the air flow reaching zero and the point where the acetone level started to decline.

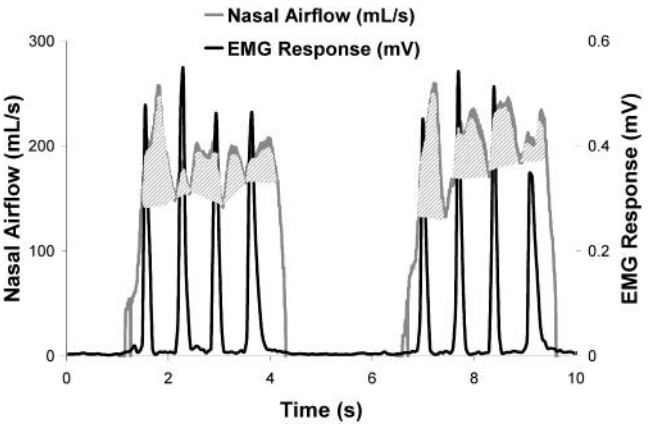

Figure 2. The Electromyography (EMG) response and nasal airflow as a panelist chewed chewing gum four times per exhalation; the panelist was instructed not to chew during inhalations. Each individual gray shaded area, from trough to trough of the nasal airflow trace, represents the sum of the volume of air pumped (jaw closure) into the gas stream and the volume of air sucked (jaw opening) out of the gas stream.

alignment procedure was carried out for all experiments described hereafter.

Influence of Mastication on Nasal Airflow. Figure 2 shows the nasal air flow and the EMG trace as panelists consumed an ethyl butyrate solution while chewing four times per exhalation on an unaromatized piece of chewing gum (in this experiment, ethyl butyrate release was not measured). After a little practice, panelists were able to chew to this pattern in a consistent and regular way. **Figure 2** shows the data for two exhalations that occurred between about 1−4.5 s and 6.5−9.5 s. The four chews per exhalation can clearly be seen on the EMG trace, while nasal airflow fluctuated across one breath cycle and the changes that occurred were associated with each EMG peak (i.e., each mouth movement). The patterns of chewing and nasal air flow were fairly regular, confirming that the panelists had maintained the set eating protocol for these samples.

With no food in mouth and no chewing, air flow rate across each breath cycle is regular, with a distinct increase to a maximum plateau value, followed by a decrease as the exhalation ends. **Table 1** shows data on the air flow during normal breathing and the air flow rate as the panelist masticated a piece of gum. The amount by which the airflow fluctuates from the mean (plateau) is represented by percentage coefficient of variances (percent CV) and it is clear that during normal breathing conditions there is a low percent CV, representing a constant airflow. However, when the panelist masticated a piece of gum throughout an exhalation, the percent CV was higher. This shows that the process of mastication caused the airflow rate to fluctuate, which was not seen during the normal respiration cycle.

Table 1. The Mean Airflows during Exhalation as Five Panelists Breathed Normally, without Any Significant Mouth Movements, and as They Masticated a Piece of Gum

	normal breathing		breathing & masticating	
panellist	mean airflow (ml/s)	% CV[a]	mean airflow (mL/s)	% CV
1	72	5	97	17
2	95	4	162	9
3	221	3	125	15
4	211	4	133	23
5	208	3	119	17
mean	161	4	127	16
std dev	72	1	24	5

[a] The % CV indicates the fluctuation of airflow throughout exhalations, (the higher the % CV the greater the fluctuation).

The fluctuations in **Figure 2** suggest that the mastication cycle affected the nasal airflow, a trend seen in all the panelists data sets. This trend could be attributed to jaw closure and opening. During jaw closure, the volume of the mouth decreases, which may push some air out of the mouth and into the pharynx. If this occurred during an exhalation, the tidal flow of air from the lungs would receive an additional pulse of air, causing an increase in the nasal airflow rate. Conversely, jaw opening would cause small volumes of air to be drawn from the pharynx into the mouth. This would remove part of the expired air stream, causing the flow rate to decrease. Looking closely at **Figure 2**, each increase in nasal airflow occurs just after an EMG event, and because an EMG peak represents jaw closing, the data support the hypothesis of air pumping into the nasal air flow on jaw closing. Further inspection of **Figure 2** reveals decreases in nasal airflow at some points that are thought to coincide with jaw opening. This activity occurs mainly under gravity with no resulting EMG signal, so it is not possible to identify the exact time that jaw opening occurs. The observations support the results of Buettner (*5*) in that the seal between the mouth and the pharynx (formed by the velum and the base of the tongue) opens intermittently during mastication, consistent with air movement in to and out of the mouth.

Further analysis of the data in **Figure 2** can provide estimates of the volumes of air associated with the air movement between the mouth and pharynx during mastication. This was achieved by integrating the area from trough to trough of the nasal airflow curve (see gray shaded areas in **Figure 2** and the values for five panelists carrying out eight replicates each in **Table 2**). It should be noted that these experiments sampled the airflow from only one nostril to achieve maximum temporal resolution for the analysis of aroma compounds. If both nostrils were sampled, turbulence at the point where the two airflows joined caused the aroma peaks to be poorly resolved. Therefore, as only one nostril was sampled, only half the airflow was measured (because the airflow flow through the upper airways splits and exits through each nostril). To simplify the calculation, it was assumed that an equal volume of air exited each nostril during an exhalation. Thus, the estimated volume (transfer volume) was multiplied by two, to account for the volume of air that exited both nostrils.

Table 2. The Combined Average Volume of Air Pumped from the Mouth to the Throat during Both Jaw Opening and Closure Actions for 5 Panelists[a]

panellist	avg chew vol (ml)
1	26
2	38
3	20
4	18
5	30
avg	26
std dev	8
% CV	30

[a] Assuming each action (jaw closure or jaw opening) moves the same volume of air, they would both be responsible for transferring 13 mL from the mouth to the pharynx and vice versa. The value for each panelist is the mean of eight replicates and has been corrected for the airflow exiting two nostrils, as only one nostril was sampled.

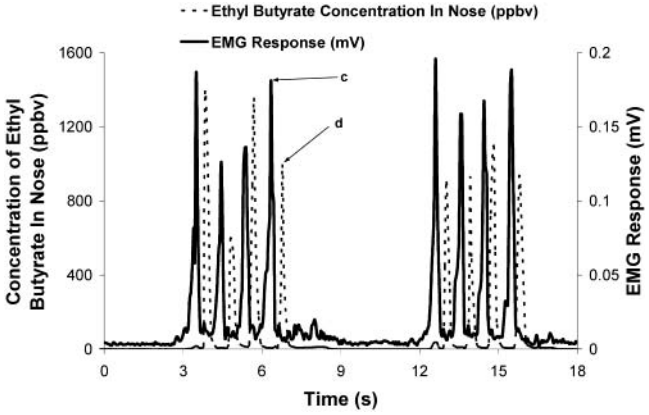

Figure 3. The relationship between mastication events and ethyl butyrate breath concentration for panelist 1. Ethyl Butyrate solution (100 ppm) was pumped (5 mL/min) into the mouth while a nonaromatized piece of chewing gum was chewed. The panelist was instructed to chew four times only during exhalations. The aroma (ethyl butyrate) pulses detected in the nose (d) follow the chew events (c).

The mean volume of air pumped between the mouth and the pharynx during each chewing event (the transfer volume) was estimated to be 26 mL and consisted of the sum of the volume of air pumped into the gas stream (jaw closure) and the volume of air sucked out of the gas stream (jaw opening). Assuming that jaw closure and jaw opening cause equal volumes of air to be transferred, each would move approximately 13 mL of air. To our knowledge, the only published data with which this value can be compared are those provided by Land (*18*). He quoted a figure of 5 to 15 mL for the transfer volume on swallowing, but since these data were obtained from preliminary experiments (for which there are no detailed experimental protocols or results) they need to be treated with caution.

Influence of Mastication on Aroma Release and Delivery. **Figure 3** shows the relationship between the release profile of ethyl butyrate and the EMG data. Again, the panelist was instructed to avoid chewing during inhalations to simplify the profile. Ethyl butyrate was chosen as the volatile due to its low persistence in the breath (*19*), which would ensure good temporal resolution of the peaks. Each EMG peak represents a chewing (jaw closure) event, and each one of these was followed by a burst of aroma detected in the air sampled from the nose. Again, this trend was seen for all the panelists involved in the study. The peaks of ethyl butyrate were therefore observed at times corresponding to the peaks in the nasal airflow rate described in the previous section. Therefore the "pulses" of air observed in **Figure 2** each contained a pulse of ethyl butyrate, which was present in the mouth and was delivered to the pharynx in the gas phase. This was subsequently delivered to the nasal cavity. These findings show that the mastication process does "pump" pulses of aroma to the nose, and the pulses shown here are not associated with swallowing events. Although this may seem to be in disagreement with the data from Buettner (*4*), the experimental protocols in the two studies were different. In our study, the solution of ethyl butyrate was pumped continually into the mouth and "chewed" as the panelist had a piece of gum to masticate. In contrast, Buettner placed an aliquot of solution in mouth and asked panelists to move it around the mouth. These differences in eating protocols may account for the observed differences in aroma transfer that were attributed to *swallowing* (in the case of Buettner), whereas, in this paper, they are the result of *mastication* events.

Table 3. Calculated Times for Volatile Transfer from the Point of Maximum Masseter Muscle Activity to Detection by APCI-MS as the Volatile Exited the Nostril[a]

panellist	replicates	volatile transmission time (s)	volume of retronasal pathway (ml)
1	12	0.29	70
2	12	0.17	66
3	12	0.17	69
4	12	0.26	77
5	12	0.39	78
	mean	0.26	72
	std dev	0.09	5
	% CV	36	7

[a] An estimate of the volume of the retronasal route was made using the transmission time and the mean nasal airflow rates of each panelist. Values for the volume of the retronasal route have been adjusted to compensate for the use of only one nostril during sampling.

Simultaneous measurements of volatile release and EMG indicated that there was an offset between the breath ethyl butyrate trace and the EMG trace, with the EMG signal (**c** in **Figure 3**) preceding ethyl butyrate detection (**d** in **Figure 3**). This offset represents the transmission time of the volatile from mouth closure through the upper airways to the nostril. Assuming that the maximum EMG value indicated full mouth closure, the temporal offset between the EMG peak and the aroma peak was estimated from the traces; results are listed in **Table 3**. The temporal offset was combined with the nasal airflow rate to estimate the volume of air delivered through the upper airways between these two events (**Table 3**). The estimated volume of the retronasal pathway was calculated as follows:

$$\text{Retronasal Volume (mL)} = (d - c) \times \text{mean airflow between } d \text{ and } c \text{ (mL/s)}$$

where d = the time of the ethyl butyrate pulse detected in the nose after the chew (s) and c = the time of the EMG peak preceding the chew (s).

This calculation was repeated for all of the eight chew events, and a mean volume was determined (**Table 3**). The mean estimated volume was 72 mL, but it is not clear which part of the retronasal route is included in this volume, as the precise location of the "plug" of volatile at the point of maximum muscular activity cannot be determined. However, considering that the volume of the nasal cavity has been estimated as 14.6 mL (*20*), the remaining volume of 57 mL could have represented part of the pharynx and mouth.

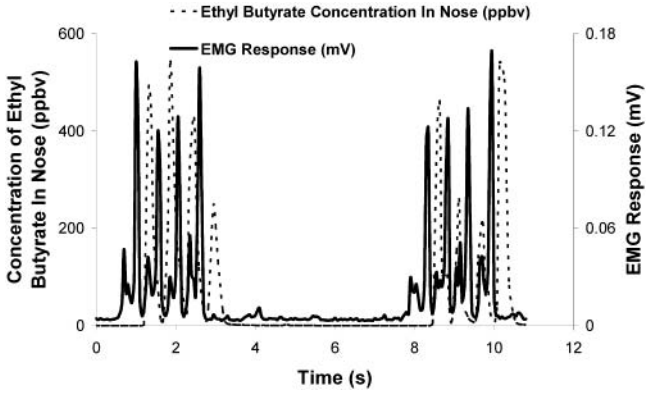

Figure 4. The relationship between mastication events and ethyl butyrate breath concentration for panelist 3. Ethyl Butyrate solution (100 ppm) was pumped (5 mL/min) into the mouth, while a nonaromatized piece of chewing gum was chewed. The panelist was instructed to chew four times only during exhalations.

The time taken for the plug of volatile to travel through the upper airways (**Table 3**) was fairly consistent between panelists, apart from panelist five. However, it transpired that this panelist was nasally impaired and could only exhale out of one nostril. It would therefore take this person twice as long to exhale the same volume of gas out of only one nostril compared to two (assuming the same flow rate). However, the estimated volume associated with this panelist's retronasal route (78 mL) is consistent with the other panelists (mean 72 mL).

Some panelists exhibited a slightly different EMG profile, in that there was a smaller peak, on the EMG trace, preceding each chew event (**Figure 4**). This can be attributed to the EMG equipment picking up the activity of other muscles in the mouth. The tongue is a large muscle, used to manipulate and position the bolus between the teeth prior to jaw closure actions; therefore, it is possible that the EMG equipment was picking up activity from the tongue. However, this had no effect on the release profile of ethyl butyrate.

The results show that the chewing action can deliver aroma compounds to the nasal cavity in a fairly regular way, and this is likely to have an influence on the overall perceived flavor of a food, particularly during phases where neither the food bolus nor aqueous phases (such as excess saliva) are swallowed.

Influence of Swallowing On Aroma Delivery. Previous studies on the swallowing process (*8*) revealed that it occurred in four phases.

1. The oral preparatory phase — related to the mastication of the food in the mouth.

2. The voluntary phase — the tongue propels the bolus posteriorly, initiating the reflexive swallow.

3. The pharyngeal stage — the bolus is then transferred through the pharynx, controlled by a series of physiological responses:

- Elevation and retraction of the velum, closing the velopharyngeal port, preventing food from entering the nasal cavity.
- Initiation of pharyngeal peristalsis to pick up the bolus and carry it through the pharynx to the cricopharyngeal sphincter, just above the esophagus.
- Elevation and closure of the larynx at all three sphincters; the epiglottis, false vocal folds, and true vocal folds.
- Relaxation of the cricopharyngeal sphincter, allowing the bolus to pass into the esophagus.

4. The esophageal phase — esophageal peristalsis carries the bolus into the stomach.

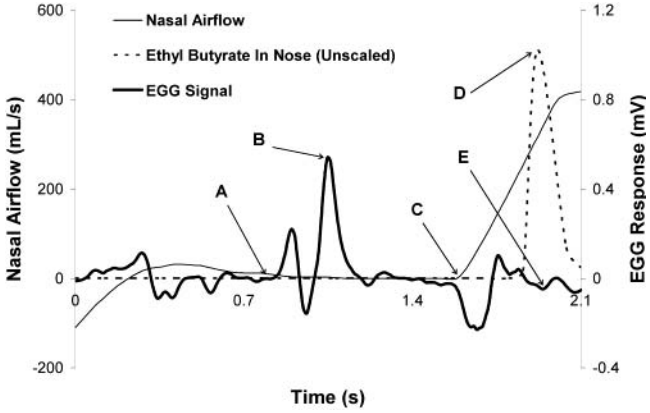

Figure 5. The relationship between the pharyngeal stage of swallowing (EGG response), nasal airflow, and ethyl butyrate release (unscaled) during the consumption of an orange drink, where: A = onset of the pharyngeal stage of swallowing, B = vocal fold closure, C = onset of the exhalation following the swallow, D = pulse of ethyl butyrate detected in the nose after the swallow (60 ppbv), E = end of pharyngeal stage of swallowing.

Figure 5 shows the EGG trace showing the relationship between the pharyngeal stage of swallowing, nasal airflow, and the volatile in nose. This trace consisted of two sharp peaks at the beginning of the pharyngeal stage (A in **Figure 5**). The more intense second peak (B in **Figure 5**) corresponds to vocal fold closure (*16*), a physiological response preventing food or liquid from entering the larynx. The smaller peak (between A and B in **Figure 5**) could be associated with downward movement of the epiglottis. A wide trough followed by a small peak signified the end of the pharyngeal stage of swallowing.

Throughout this stage of the swallowing process (A to C in **Figure 5**) there was no air movement through the upper airways (*8*−*10*) for all the panelists involved in the study. This was associated with the closure of the pharynx from the larynx, achieved by closure of the vocal folds. Elevation of the velum also prevented airflow through the upper airways. This lack of air flow during swallowing casts doubt on the "swallow breath" concept proposed by Land (*18*). However, the act of swallowing is almost always followed by an exhalation (*9*), which is in agreement with our data, and it is this exhalation that is responsible for transporting volatiles from the pharynx to the nasal cavity. Hence, pulses of volatile are delivered to the nasal cavity *after* the pharyngeal stage of swallowing, and not during.

In **Figure 5**, there is an offset between the start of expiration following the swallow (C in **Figure 5**), and the aroma exiting from the nostril (D in **Figure 5**), which is dependent on the volume of the upper airways and the flow rate. This transmission time was calculated (**Table 4**) and a mean value of 0.38 s obtained for the passage of aromas from the pharynx to the nasal cavity. The mean nasal airflow between the onset of expiration and the aroma peak was estimated halfway up the nasal airflow curve (**Figure 5**) and used to calculate the volume of air expelled from the upper airways between these two time points (**Table 4**). A similar calculation was used as in the previous experiment to calculate the volume of the retronasal pathway

$$\text{Retronasal Volume (mL)} = (D - C) \times \text{mean airflow between } D \text{ and } C \text{ (mL/s)}$$

where D = the time of the ethyl butyrate pulse detected in the nose after the swallow (s) and C = the time of the start of the exhalation following the swallow (s).

Table 4. The Mean Time Taken for the Aroma Compound to Exit the Nose from the Pharynx[a]

panellist	replicates	volatile transmission time (s)	volume of retronasal pathway (ml)
1	4	0.38	24
2	8	0.37	80
3	5	0.46	56
4	5	0.36	36
5	6	0.33	42
	mean	0.38	48
	std dev	0.05	21
	% CV	12	45

[a] An estimate of the volume associated with the retronasal route was made using the nasal airflow rate. The values have been adjusted to compensate for the sampling of only one nostril.

This calculation was repeated for each replicate to give a mean estimate of the volume associated with the retronasal route (**Table 4**). The error associated with this estimate (48 mL) is large (45% CV), which could be attributed to either variation in the estimated nasal airflow or physiological differences between panelists. The two estimates of the retronasal volume vary between 72 mL (mastication data) and 48 mL (swallowing data). These estimated volumes correspond to similar, but not necessarily identical, retronasal pathways. The mastication pathway could consist of the mouth, pharynx, and nose, whereas the swallowing pathway may include only the pharynx and the upper airways. The process of mastication involves the gas phase transfer of volatiles from the mouth to the pharynx where they are swept through the upper airways to the nose by expired air from the lungs. However, the mechanism of swallowing is slightly different, in that the liquid or bolus is forced into the pharynx by the tongue, possibly with small amounts of air as well. As soon as this material enters the pharynx, the velum retracts and elevates, preventing material from entering the nasal cavity (velopharyngeal port closure). While the material is in transit through the pharynx, volatile compounds partition into the air within the pharynx and form a "plug" of volatile. The velopharyngeal seal remains closed until the material has entered the esophagus. This then allows the vocal folds and velopharyngeal port to open, allowing expired air to deliver the plug of volatile to the nose.

The mechanism of swallowing plays a vital role in delivering the perceived aroma of a beverage. However, during the consumption of solid foods, both mastication and swallowing contribute to the delivery of the perceived aroma. The relative importance of each event may vary according to the foodstuff being consumed and the regularity of each process. The technique developed may prove useful for studying dysphagia and other related swallowing disorders in the future, as it is noninvasive, mobile, and easy to operate. The rehabilitation of patients suffering from aspiration could be followed as the technique monitors air movement throughout the swallowing process.

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