Particle Size Distribution of Food Boluses after Mastication of Six Natural Foods
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What is This?
INTRODUCTION

The primary role of mastication is to transform a mouthful of food into a bolus ready for swallowing (Lillford, 1991; Prinz and Lucas, 1995). The subject achieves this by reducing the food to small particles and by lubricating it with saliva and any liquid released from the food itself. A cohesive mixture is formed in the food bolus from liquid-coated particles that cohere by viscous adhesion. The resulting entity can flow smoothly down the pharyngeal walls during deglutition (Lucas and Luke, 1986; Prinz and Lucas, 1995) and prevents stray particles from entering the trachea (Prinz and Lucas, 1995; Alexander, 1999). Exactly how particle size reduction triggers swallowing is unclear. The process has been claimed to depend on food type (Prim and Lucas, 1997; Hoebler et al., 1998, 2000) and on bolus size (Lucas and Luke, 1984; Buschang et al., 1997). We tested the hypothesis that particle size is an important triggering factor for deglutition, and thus there is no difference in particle size between and among individuals.

In this study, we determined the particle size distribution of the boluses collected before swallowing to test for variability between and among individuals. Six different natural foods—3 nuts and 3 fresh raw vegetables—were chewed by ten healthy adults. We used two methods, sieving and laser diffraction, to measure the particle sizes in the food boluses after mastication.

MATERIALS & METHODS

Ten subjects with a healthy dentition (six females, four males, aged 36.7 ± 9.5 yrs) were selected on the basis of strict dental criteria (Lassauzay et al., 2000). Informed consent was obtained according to the guidelines of the ethical committee of the Université d’Auvergne. Two groups of foods were studied. The first included peanuts, almonds, and pistachios (dry nuts, 9% water) and the second carrots, radishes, and cauliflower (raw vegetables, 87% water). Portions consisted of 3 nuts (peanut, almond, pistachio) and 3 vegetables (cauliflower, radish, and carrot) were chewed and expectorated after self-estimated complete mastication. Measurements with sieving and laser diffraction methods indicated that particles were much larger in vegetables than in nuts. Particle size distributions were similar among nuts and among vegetables. Surprisingly, no inter-individual variability was observed in the particle distributions for the 6 foods, although several sequence variables differed markedly. A need for a bolus to be prepared with a precisely determined texture before it can be swallowed may explain the inter-subject variability of the masticatory function.

KEY WORDS: mastication, food bolus, particle size, swallowing.
cycles (Sieve-Bolus4). For measurement by laser diffraction, 2 boluses (Laser-Bolus1 and Laser-Bolus2) resulting from complete mastication were collected in a second session.

For particle size measurements by the sieving method, the expectorated boluses were washed on the 0.4-mm sieve for 1 min in running water and dried (40°C, 1 hr). The boluses were then poured through a stack of 7 sieves with apertures of 4, 2.5, 2, 1.4, 1, 0.8, and 0.4 mm (Saulas, Paisy Cosdon, France). The fractions retained on each of the 7 sieves were weighed, and the weights were expressed as a percentage of the weight of the mouthful before mastication. We achieved particle size measurements of Laser-Bolus1 and Laser-Bolus2 by laser light diffraction using a Mastersizer S (Malvern Instruments Ltd, Malvern, UK) equipped with a 1000-mm lens, allowing for analysis of particles between 5 and 2000 μm. Particles larger than 2 mm were eliminated from Laser-Bolus1 and 2 by means of a 2-mm sieve. This method expressed size distributions as a percentage of the total volume occupied in the laser chamber by the particles. The volume was converted to weight with the use of volumetric mass and expressed as cumulative values. The 5-μm- to 2-mm-diameter range of particle sizes was divided into 17 classes for analysis.

Statistical analyses were performed by SAS®. The distribution was normal in all cases, and a one-way or two-way analysis of variance was performed. When ANOVA indicated a significant difference, a Student Newman-Keuls test was performed at a risk of 5%.

RESULTS

Sieving: Sieve and Bolus Type (Sieve-Boluses1 to 4) as Factors, Weight as Measured Variable

The weights of all foods collected after mastication represented only a fraction of the initial mouthful. Approximately 40% of the initial weight was recovered for Sieve-Boluses1 and 2, and 60% and 80% for Sieve-Boluses3 and 4, respectively (Table). A two-way ANOVA [boluses (Sieve-Boluses1 and 2) and sieves (n = 7) as factors] was performed for each of the 6 foods. It indicated, for each of the 6 foods, that: (1) the total weights of Sieve-Boluses1 and 2 were similar (p > 0.05); (2) the weight collected in the 7 sieves varied significantly (22 ≤ F ≤ 41, p < 0.001); and (3) there was no significant difference in the distribution of particles among the sieves between Sieve-Boluses1 and 2, since no interaction between bolus and sieve factors was observed (p > 0.05). The reduction of the number of masticatory cycles to one-half (Sieve-Bolus3) and one-quarter (Sieve-Bolus4) induced a corresponding increase in the total weight of the bolus (16 ≤ F ≤ 33, p < 0.001, Table), together with a different distribution of particle sizes in favor of the largest ones (Fig. 1).

Sieving: Subject as Factor, Weight as Measured Variable

No inter-individual variability was noted in any of the 24 one-way ANOVAs (6 foods x Sieve-Boluses1 to 4; 0.29 < p < 1).

Distribution of the particle size across sieves was also similar for all subjects, regardless of the nature of the chewed food (0.5 < p < 0.69 for 6 two-way ANOVAs, with subject and sieve as factors). This was in contrast to the inter-subject variability of every time-related parameter. For example, sequence duration differed across the 10 subjects (range, 6.5-42.4 sec), depending on the food (6 one-way ANOVAs with subject as factor and sequence duration as measured variable). Masticatory frequency also differed across the 10 subjects, ranging from 1.53 ± 0.23 to 1.92 ± 0.27 Hz (p < 0.001 for 24 one-way ANOVAs with subject as factor). Masticatory frequency varied neither with food (p > 0.05 for the 6 one-way ANOVAs) nor with the type of bolus (p > 0.05 for the 4 one-way ANOVAs).

Table. Weight of the Food Boluses Expectorated after a Complete Masticatory Sequence (Sieve-Boluses1 and 2), Half a Sequence (Sieve-Bolus3), or a Quarter Sequence (Sieve-Bolus4)

<table>
<thead>
<tr>
<th></th>
<th>Sieve-Bolus1</th>
<th>Sieve-Bolus2</th>
<th>Sieve-Bolus3</th>
<th>Sieve-Bolus4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peanut</td>
<td>37.0 ± 2.8</td>
<td>36.0 ± 3.4</td>
<td>58.0 ± 5.1</td>
<td>79.6 ± 3.4</td>
</tr>
<tr>
<td>Almond</td>
<td>47.4 ± 3.8</td>
<td>48.7 ± 3.2</td>
<td>67.2 ± 4.6</td>
<td>85.3 ± 3.7</td>
</tr>
<tr>
<td>Pistachio</td>
<td>38.4 ± 2.8</td>
<td>36.9 ± 3.5</td>
<td>56.6 ± 4.1</td>
<td>76.5 ± 4.0</td>
</tr>
<tr>
<td>Carrot</td>
<td>40.2 ± 5.9</td>
<td>38.3 ± 4.4</td>
<td>58.0 ± 4.1</td>
<td>74.9 ± 3.5</td>
</tr>
<tr>
<td>Radish</td>
<td>37.8 ± 5.6</td>
<td>37.0 ± 4.6</td>
<td>62.5 ± 6.0</td>
<td>82.6 ± 4.3</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>40.7 ± 5.9</td>
<td>35.6 ± 3.7</td>
<td>58.4 ± 5.5</td>
<td>79.5 ± 4.0</td>
</tr>
</tbody>
</table>

a Values are expressed as the percentage of the initial weight before mastication.
b The 6 one-way ANOVAs (one per food) were significant (p < 0.001).
c Values are expressed as mean ± standard error of the mean (n = 10 in all cells).
d Student Newman-Keuls tests were performed at a risk of 5%. Different letters (x, y, or z) in the same row indicate a significant difference between and among the different boluses of the considered food.
Particle diameters were not distributed at random ($p < 0.001$), and both total weights and the diameter distribution did not differ between Laser-Boluses1 and 2 (two-way ANOVA for each food, with bolus type and diameter class as factors). Again, no significant difference between and among subjects was noted (12 one-way ANOVAs, Laser-Boluses1 and 2 x 6 foods, $p > 0.05$). As observed with sieving, particles were not evenly distributed in the diameter classes ($p < 0.001$ for diameter class). No difference was observed between the total weight of the boluses ($p > 0.05$ for food type), and particle diameter distributions differed between and among foods ($p < 0.001$ for interaction, two-way ANOVA, Fig. 2).

**Full-spectrum Representation of Particle Size Distribution**

The sieve method analyzed the bolus particle sizes above 0.4 mm, whereas the laser diffraction method could be used only for particles below 2 mm. This defines three measurement intervals ($5 \mu m < size < 0.4 \text{ mm}; 0.4 \text{ mm} < size < 2 \text{ mm}, size > 2 \text{ mm}$). The full distributions were calculated for the 6 foods by two equations with two unknowns for the percentages measured with sieving and laser diffraction methods (Fig. 3). In doing this, we assumed that the particle size distributions were representative of the collected bolus in both methods.

**DISCUSSION**

The results of this study show: (1) that, after complete mastication, the weight of the food boluses was only 40% of the initial weight of the food sample; (2) that particle size distributions depended on food type, a large difference between nuts and vegetables being observed, whereas strong similarity was found within each of these two groups; (3) that there was little or no variability between and among individuals in particle size; and (4) that different methods are needed to characterize the particle size distribution more accurately.

**Weight of Food Boluses before Being Swallowed**

The boluses collected after complete mastication had lost nearly 60% of the initial weight of the food samples, for all foods or subjects. The amount of loss might be different in normal, not expectorated, boluses. However, intermediate swallowing probably accounts for this marked loss of particles. The weight loss may result from the transportation of bolus fractions, but also from the liquid content liberated by the food and loaded with soluble nutrients. According to
several authors, intermediate swallows, which occur in nearly 80% of masticatory sequences, are characterized by several transportsations of food fractions to the oropharynx, operated by tongue-palate contact during protraction of the tongue and hyoid (Palmer et al., 1992; Hiiemae et al., 1996; Hiiemae and Palmer, 1999).

**Particle Size Distribution Depends on Food Type**

The 6 foods analyzed in this study resulted in two particle size distributions. Raw vegetables were transformed into boluses made up of particles larger than 2 mm, and nuts gave a bolus which contained 90% of particles smaller than 2 mm (Fig. 3). A special food index based on mechanical properties of a large array of foods was shown to correlate with the breakdown properties observed after a single stroke (Agrawal et al., 1997). It is also correlated with the electromyographic activities recorded during mastication of the same product (Agrawal et al., 1998). This food index, which takes into account important characteristics such as water and fiber content, separated nuts from raw vegetables and reflects the differences in particle size distribution observed in this study.

Analysis of our data shows that deglutition is triggered in spite of very different particle size distributions. Thus, other parameters must be at work to inform the swallowing center of the need to operate. Prinz and Lucas (1997) have proposed that particle size reduction by increasing the surface tension, insalivation, by adding viscosity within the bolus and optimal duration for preparing the bolus inside the mouth are the main factors that determine the rheological properties of the bolus. The perception of the resulting bolus cohesion and plasticity may, in turn, be the key factor to triggering a safe swallow.

**Significance of the Small Inter-individual Variability in Bolus Composition**

Variability between and among subjects is a major characteristic of the physiology of human mastication. This variability has been observed, for example, in cycle shape, amplitude of muscular contraction, duration of masticatory sequences, number of masticatory cycles, and masticatory frequency (Pröschel and Hoffmann, 1988; Lassauzay et al., 2000) and was confirmed in this study. It could not be eliminated by the use of strict dental criteria or rheological control of the food (Lassauzay et al., 2000; Peyron et al., 2002). The most striking result of the present study is that the size distribution of bolus particle for a given food type was similar in the 10 subjects. This means that the requirements that the food bolus must meet before it is ready to be swallowed are similar for everyone. These requirements may strongly depend, for each food type, on a certain bolus particle size. Until the mandatory particle size is reached, swallowing may be inhibited and chewing prolonged. The wide inter-individual variability displayed by electromyographic activity and masticatory kinematics (Pröschel and Hoffmann, 1988; Lassauzay et al., 2000) may therefore be explained by the individuals’ need to adapt their chewing strategy to their personal anatomical features and
acquired sensori-motor patterns and conditionings. Several properties other than particle size—for example, lubrication, plasticity, or modification of the structure of meat—may also be included in the required properties of the pre-swallow bolus (Hutchings and Lillford, 1988; Lillford, 1991; Prinz and Lucas, 1995; Alexander, 1999; Mioche et al., 2002).

**The Rationale for the Use of Different Methods**

Several methods can be used to measure particle size, including microscopy and image analysis, sedimentation analysis, diffusion of light, sieving, and laser diffraction (Shi et al., 1990; Mahmood et al., 1992; Van Der Bilt et al., 1993; Hoebler et al., 1998, 2000). Sieving and laser diffraction were chosen here because their combined use widens the range of analysis from 5 μm to 4 mm. Laser diffraction appeared to be the most suitable method for measuring the granularity of dry and brittle foods, since these foods contain a high percentage of particles under 400 μm. Food boluses of raw vegetables made up of larger particles can also be characterized by sieving. Other kinds of foods would certainly need other approaches. For example, some foods break not into regular spherical particles but into fibrous spines. Hence, examining particle shapes with image analysis might be the best method (Shi et al., 1990; Hoebler et al., 1998, 2000). In other cases, the observation of either the softening or the dissolution of the bolus rather than its breakdown might be appropriate.

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**REFERENCES**


