Received: 30 August 2021 | Revised: 23 February 2022 | Accepted: 25 February 2022

DOI: 10.1111/jtxs.12671

RESEARCH ARTICLE

Journal of Texture Studies WILEY

# The effect of bolus size on masticatory parameters at swallowing threshold in children using a hard, solid, artificial test food

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**Funding information**
Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT), Universidad Nacional Autónoma de México, Grant/Award Number: IN-231320

## Abstract

The effect of different bolus sizes on food breakdown has been studied in adults, but not in children. The objective of this study was to study median particle size (MPS) and other parameters of masticatory function at swallowing threshold (ST) in 8–10-year-old-children with two different bolus sizes. A randomized crossover trial was undertaken in 89 eight to ten-year-old children. The study was performed with informed consent and ethical approval. The artificial test food used was made of a condensation silicone (Optosil Comfort) following a standardized protocol. Two bolus sizes (three or four quarters of a 20-mm diameter, 5-mm thick tablet) were randomized to avoid an order effect and tested in different sessions. Variables were: MPS ($X_{50}$) at ST, number of cycles until ST, sequence and cycle duration as well as cycles/g. Comparisons were performed with paired *t* and Wilcoxon tests, regressions and correlations were run. Cutoff for statistical significance was .05. Statistically significant differences were found for all variables; $X_{50}$ (2.5 ± 0.8 vs. 2.8 ± 0.7 mm, $p < .001$), cycles until ST (38 vs. 40, $p = .022$), sequence (25 vs. 27 s, $p = .003$), and cycle duration (650 vs. 683 ms, $p = .015$) and cycles/g (27 vs. 21 cycles/g, $p < .001$), three or four quarters, respectively. In conclusion, in children, as in adults, chewing on a bigger bolus size leads to a larger MPS ($X_{50}$) at ST. When chewing on a larger bolus the number of cycles increases, but not enough to swallow the same particle size since the number of cycles/g is less with a bigger bolus size.

KEYWORDS
bolus size, children, food breakdown, mastication, median particle size, swallowing threshold

## 1 | INTRODUCTION

The main objective of mastication is to break down ingested food, mix it and form a cohesive bolus so that it can be safely swallowed. The overall process of food breakdown, the composite result of selection and breakage (Lucas & Luke, 1983), is reflected in the reduction of the median particle size (MPS), $X_{50}$, with the number of chews. A subject's ability to break down food particles after a particular number of chewing cycles is known as masticatory performance (MP; Bates, Stafford, & Harrison, 1976). A subject's MP using a solid test food is usually defined as the $X_{50}$ value reached after a particular number of chews (van der Bilt, Olthoff, van der Glas, van der Weelen, & Bosman, 1987; Gonçalves et al., 2021). In the present study, $X_{50}$ is determined at the swallowing threshold (ST) which is reached after a subject-specific number of chews. While particle-size reduction, reflected in the value of $X_{50}$, is related to ease of swallowing, particle surface area is more relevant to gastrointestinal digestion (Lucas & Luke, 1984; Sheine & Kay, 1982). The inverse value of $X_{50}$ ($1/X_{50}$) is approximately proportional to the surface-to-unit of volume ratio of the food particles (Lucas & Luke, 1984). Another variable used in the present study is the ratio of the number of chews to swallowing per unit volume (weight) of food (chews/g food). The chew/g ratio characterizes two aspects of food processing as follows: (a) the greater the ratio value, the greater the degree of intraoral processing of a chewing sample until ST and (b) the smaller the ratio, the greater the rate at which food is delivered weight for weight as a source of metabolic energy to the gastrointestinal tract for further digestion (Lucas & Luke, 1984).

Each chewing cycle of solid food starts with selection that represents the sum action of all factors involved in collecting the particles and placing them between the occlusal surfaces to be fractured. Breakage deals with the actual fracture of selected particles into fragments of variable number and size. Anatomical/physiological- and food-related factors influence both processes (van der Glas, Kim, Mustapa, & Elmanaseer, 2018; Liu, Wang, Chen, & der Glas, 2020). Two food-related factors are important in selection, that is, the size and the initial number of the particles in a chewing sample. Larger particles are more easily collected by the tongue and/or trapped between antagonistic teeth than smaller ones during habitual chewing. The probability of selection also depends on the number of particles due to a limited number of breakage sites available on a limited number of antagonistic posterior teeth. Due to an increase in the saturation of the breakage sites, the chance of being selected decreases as the number of particles in a food sample increase. The value of $X_{50}$ therefore increases (i.e., MP decreases) for any number of chews when chewing samples with more particles (Liu, Wang, Chen, & van der Glas, 2018). When comparing $X_{50}$ after 20 chewing cycles in adults with two, three or four quarters of a tablet of an artificial test food (Optosil), a significant difference in $X_{50}$ was found between the three boli (2.1 ± 0.7 mm with two; 2.5 ± 0.5 mm with three, and 2.9 ± 0.6 mm with four quarters; Buschang, Throckmorton, Travers, & Johnson, 1997). A decrease in MP with an increase in the initial number of particles has not only been observed with the artificial test food Optosil in adults (Liu et al., 2018), but also with the use of peanuts as a natural food (Lucas & Luke, 1984). To the best of our knowledge there are no studies comparing food breakdown with different bolus sizes or number of particles in children.

Food portions have increased over the years (Nielsen & Popkin, 2003; Piernas & Popkin, 2011; Steenhuis, Leeuwis, & Vermeer, 2010). Hamburgers for example, increased from 161 to 198 g and French fries' portions increased from 88 to 102 g between 1977 and 1996 (Nielsen & Popkin, 2003). When adults are offered larger portions of food bolus size increases (Burger, Fisher, & Johnson, 2011); information on this issue in children is scarce but children consume more food when presented with large portion sizes (Ello-Martin, Ledikwe, & Rolls, 2005). Two studies, one in preschool children (Fisher, Rolls, & Birch, 2003) and one in 8–10-year-old children (Gómez-Zuñiga, 2020) have reported that the bite size of natural foods increases with a larger portion size.

In addition to forming a food bolus that can be safely swallowed, the objective of particle size reduction during chewing is to increase the food's surface area allowing bioaccessibility of nutrients. This bioaccessibility might be affected when larger food boli with larger numbers of particles are involved. It is therefore important to examine the particle size distribution at the ST. In a chewing test until swallowing, ST is the moment when a subject is ready to swallow the food (Gonçalves et al., 2021). Instead of actually swallowing, the subject then spits out the chewed particles to allow for an analysis of the particle size distribution. While $X_{50}$ is greater for a chewing sample containing more particles, than one with fewer particles at the same number of chews, the slower rate of particle size reduction with more particles could be compensated for by performing more cycles, reducing $X_{50}$ to the same level. Although the number of chews performed to ST increases with the number of particles in a food bolus, reflecting some size reduction by prolonged chewing, $X_{50}$ remains larger than $X_{50}$ with fewer particles in adults (Lucas & Luke, 1984). Thus, adults do not compensate for less particle size reduction with sufficiently more chewing cycles while reaching ST. It is unknown to what extent children can compensate when chewing on a larger bolus size with more particles by performing more cycles. The first aim of the present study was to determine $X_{50}$ with two different bolus sizes (three of four quarters of a tablet of a hard solid artificial test food) at ST in children and examine the number of chews performed to ST with the two different numbers of particles in the chewing sample. Furthermore, the values of chews performed to ST/g food were compared.

Obesity is a serious health problem related not only to what we eat, but also how we eat. The bite size of obese adults is larger than that of normal weight adults (Hill & McCutcheon, 1984; Zijlstra et al., 2011) and their eating rate (grams food consumed per minute) is higher (Almiron-Roig et al., 2015). In addition, maximum occlusal force (MOF) which is inversely related to food breakdown (Lepley, Throckmorton, Ceen, & Buschang, 2011), is related to body size (Julien, Buschang, Throckmorton, & Dechow, 1996). A study in preschool children found a higher prevalence of overweight in those that did not chew well (Okubo, Murakami, Masayasu, & Sasaki, 2018). The second aim of the present study was to determine MOF in three categories of children based on body weight and to examine the relationship of MOF and body weight status with $X_{50}$ at ST and chews/g of the test food.

## 2 | MATERIALS AND METHODS

### 2.1 | Design and study participants

The main objective was tested with a within-subject crossover design. Participants in the study were 8–10-year-old children from two primary schools of the same socioeconomic level in Mexico City. Children were excluded if they had any diagnosed systemic disease, dental pain, large cavities or a very loose tooth, evident craniofacial abnormalities, a severe malocclusion (such as a clear Class III or a posterior crossbite) or behavioral problems that could complicate the testing procedure.

Ninety children were needed to provide 80% power to detect a 0.3 effect size (2.5 ± 1 vs. 2.8 ± 1 mm) in $X_{50}$ in a two tailed, paired *t*-test with an $\alpha$ of .05 (G*Power 3.1) (Faul, Erdfelder, Lang, & Buchner, 2007).

The project was presented to parents of 412 eight to ten-year-old children during parent/teacher meetings; 318 of them agreed to their child's participation and signed the informed consent forms (parents and children). After screening for selection criteria only 91 children were included. Two of these were later eliminated because they only attended one session; 47 of the children were from one school (22 girls and 25 boys) and 42 from the second school (18 girls and 24 boys).

This study was conducted in conformity with the ethical guidelines of the World Medical Association Declaration of Helsinki and was approved by the Ethics Committee of the affiliated institution of the authors (CIE/0810/11/2018). Written informed consent was obtained from all parents prior to the study; children gave their written and verbal assent.

## 2.2 | Preparation of the artificial test food

Food breakdown was evaluated with a hard, solid, artificial test food made of condensation silicone (Optosil Comfort; Heraeus Kulzer) following the manufacturer's instructions and a standardized protocol (Albert, Buschang, & Throckmorton, 2003). The silicone material was pressed (OL463; Manfredi, Italia) at 300 psi for 5 min into a template to make 5-mm thick and 20-mm diameter tablets with a hardness of 62–65 Shore A units (Digital 211 Type A Durometer). Hardness was determined based on the average of five measurements in different areas of the tablets. Tablets with the suitable hardness were cut into quarters and packed in Ziploc bags; 15 quarters were packed for the 3 quarters bolus size or 20 quarters for the 4 quarters bolus size (three quarters = 1.4 g; four quarters = 1.9 g) since the chewing process of each bolus size was repeated five times. Three quarters of a tablet is the size that has been used to evaluate food breakdown in adults as well as in children (Barrera, Buschang, Throckmorton, & Roldán, 2011; Julien et al., 1996; Toro, Buschang, Throckmorton, & Roldán, 2006). Tablets were used within 5 days after they were made.

## 2.3 | Experimental procedure

Sessions were undertaken between 1 and 3 hr after either breakfast or lunch to avoid a possible hunger effect. Children were weighed with light clothing using a portable electronic scale (BF-689; Tanita) to the nearest 0.1 kg. Height was measured with a tape attached to the wall while children were standing straight looking forwards with their backs to the wall, with no shoes and heels touching the wall. These parameters were used to determine body mass index (BMI) [body weight (kg)/ height squared ($m^2$)]. Children's nutritional status was determined according to CDC guidelines (Kuczmarski et al., 2002): obese (≥95th percentile), overweight (85th–94th percentile), normal weight (5th–84th percentile).

MOF was measured using a force transductor (Occlusal Force-Meter GM-10; Nagano Keiki, Japan). The sensitive part of the sensor was placed between upper and lower first permanent molars; the children were asked to bite as hard as they could. A disposable cap was placed on the sensor to protect children's teeth. Three measurements per side were taken; the two highest values, independently of the side, were averaged to provide the measure of their MOF.

Children were seated on a chair with no head support and asked to chew imagining they were chewing real food. This study tested food breakdown at ST, the children were therefore asked to chew until they felt that under normal circumstances, the food would be ready to be swallowed and to then stop and raise their hand. This test provides the particles in the bolus just before deglutition. They were clearly told that they should not swallow the test food and were instructed to spit it onto a paper filter and rinse with water spitting into the same filter until no more particles were left in the mouth (visual checking). Children were given a sample of the test food before the real test so they could get familiar with the procedure and the breaking down of the test food during chewing; the particles produced in the familiarization test were not analyzed. The order of the two bolus sizes tested (three or four quarters) was randomized using a dice and undertaken on two different test days with a 1-week difference. There were five repetitions of each bolus size; children could rest between repetitions if they requested to when asked. The test food was pooled, and results of the tests include all repetitions.

Chewing cycles were counted on-site by the first author. A chewing cycle is described as a cycle with an opening and closing phase as in typical cycles eliminating those clearly used to only shift or conform the bolus. Sequence duration was timed with a stopwatch from the moment the child started chewing to the moment they stopped at ST. Chewing cycle duration was determined dividing sequence duration by the number of chewing cycles during that sequence. The number of cycles/g of the artificial test food were also determined dividing the number of chews by 1.4 g for the three quarters bolus and 1.9 g for the four quarters bolus. The testing time lasted approximately 10 min per session.

## 2.4 | Processing of the chewed test food

The chewed test food was dried at room temperature and then sieved on a stack of seven sieves (5.6, 4.0, 2.8, 2.0, 0.85, 0.425, and 0.25 mm mesh/Dual MFG, Co. Inc., U.S. Standard Sieves, Franklin Park, IL) placed on a sieve shaker (Cole-Palmer SS-3CP) for 2.5 min. The particles on each sieve were weighed on a precision balance (0.0001 g, BBI-31; BOECO, Germany). The percentage of accumulated weight on each of the sieves was used to calculate $X_{50}$ (MPS) and broadness of particle distribution (BPD) for each individual, based on the Rosin–Rammler equation (Olthoff, van der Bilt, Bosman, & Kleizen, 1984).

$$Q_w = 100\left[1 - 2^{-(x/X50)^b}\right]$$

where $Q_w$ is the weight percentage of particles with a diameter smaller than $x$ (maximum sieve aperture) and $b$ is the BPD. $X_{50}$ is the aperture of a theoretical sieve through which 50% of the particles can pass. BPD is inversely related to the variation in particle size (Liu et al., 2020).

### 2.5 | Statistical analysis

Descriptive statistical procedures were performed. Data distribution was assessed inspecting skewness and kurtosis. Data are expressed as mean ± *SD* of five repetitions or as the median and interquartile range. The data was compared with paired *t*-tests or Wilcoxon signed-rank tests (three vs. four quarters), analysis of variances, Kruskal–Wallis (three groups), or independent *t*-tests (boys vs. girls). Pearson and Spearman correlations between variables were assessed. Simple and multiple linear regressions were run with $X_{50}$ with three and four quarters and cycles/g with four quarters as dependent variables. Only significant regression models are reported. Statistical procedures were performed with SPSS Version 15.0. (SPSS Inc, Chicago, IL) and statistical significance was set at $p = .05$.

## 3 | RESULTS

After screening for selection criteria and eliminating two cases with incomplete data sample size was 89; boys represented 55% of the total sample.

There were no statistically significant differences between boys and girls except for cycle duration which was longer for girls (Mann–Whitney test, $p = .038$; data not shown). Differences for variables between nutritional groups were evaluated but no consistent significant differences were found. Data were therefore pooled (Table 1).

Data for MPS ($X_{50}$) and other parameters when chewing three (1.4 g) or four quarters (1.9 g) are displayed in Table 2. There was a statistically significant larger $X_{50}$ when chewing four quarters than three quarters. Figure 1 displays the accumulated particle size distributions with a logarithmic scale for the different sieve sizes, for one child, from which $X_{50}$ and BPD are obtained. This girl's $X_{50}$ (2.69 mm),

**TABLE 1** Characteristics of the sample ($n = 89$) and group comparisons based on nutritional status

| | | Nutritional status group based on their body mass index (mean ± SD) | | | |
|---|---|---|---|---|---|
| | | **Normal weight (16.29 ± 1.39)** | **Overweight (19.11 ± 1.32)** | **Obesity (22.25 ± 2.42)** | ***p* Value** |
| | Boys | 17 | 11 | 21 | |
| | Girls | 17 | 10 | 13 | |
| MOF kN mean (*SD*) | | 0.426 (0.103) | 0.462 (0.108) | 0.417 (0.112) | .239[a] |
| MPS mm median (IQR) | 3/4 | 2.75 (1.96) | 2.49 (0.83) | 2.65 (1.06) | .643[b] |
| | 4/4 | 2.88 (1.17) | 2.54 (0.69) | 2.87 (1.07) | .177[b] |
| Cycles/gram median (IQR) | 3/4 | 24.23 (7.89) | 27.61 (12.18) | 28.31 (15.99) | .409[b] |
| | 4/4 | 19.37 (9.95) | 19.58 (13.05) | 21.95 (12.63) | .619[b] |

*Note:* Results represent five replicates.

Abbreviations: IQR, interquartile range; kN, kilonewtons; MOF, maximum occlusal force; MPS, median particle size ($X_{50}$); ¾ (1.4 g), three quarters; 4/4 (1.9 g), four quarters; *SD*, standard deviation.

[a] Analysis of variance.

[b] Kruskal–Wallis.

**TABLE 2** Effects of bolus size on median particle size and other variables tested ($n = 89$)

| | Three quarters | Four quarters | *p* Values |
|---|---|---|---|
| MPS (mm) mean (*SD*) | 2.56 (0.84) | 2.8 (0.72) | *<.001*[a] |
| BPD median (IQR) | 2.99 (1.52) | 3.17 (1.27) | *.058*[b] |
| Cycles median (IQR) | 37.6 (15.2) | 39.8 (22.9) | *.022*[b] |
| Sequence duration (s) median (IQR) | 25.66 (12.32) | 27.32 (5.98) | *.003*[b] |
| Cycle duration (ms) median (IQR) | 650.63 (126.17) | 683.17 (151.72) | *.023*[b] |
| Cycles/g median (IQR) | 26.48 (10.7) | 20.95 (12.05) | *<.001*[b] |

*Note:* Results represent five replicates.

Abbreviations: BPD, broadness of particle distribution; g, gram; IQR, interquartile range; MPS, median particle size ($X_{50}$); ms, milliseconds; s, seconds; *SD*, standard deviation.

[a] Paired Student's *t*-test.

[b] Wilcoxon signed-rank test.

when chewing on three quarters was very close to the sample's mean value (2.56 mm); BPD is 2.83. Her $X_{50}$ was 3.16 mm when chewing on four quarters; BPD was 3.82. This figure shows a larger percentage of particles on a larger sieve aperture when chewing with the larger bolus size.

More chewing cycles before ST were required with the four quarters bolus size. Statistically significant differences were also found for sequence duration and chewing cycle duration which were longer with the larger bolus size. Cycles/g were on the contrary fewer with the larger bolus size.

The correlations (data not shown) and regression models (Table 3) indicate that the correlation between MOF and $X_{50}$ is not strong but significant when chewing on three or four quarters of the test food (Rho $= -.291$ y $-.256$, respectively). The correlation between $X_{50}$ when chewing on the smaller and larger bolus is .803 and $X_{50}$ when chewing on the smaller bolus size explains 65% of the variance of $X_{50}$ with the larger bolus. The correlation between BMI and cycles until ST was significant with three quarters of a tablet, but not with the larger bolus size. Spearman correlations between cycles until ST with both bolus sizes as well as cycles/g with both bolus sizes were .707.

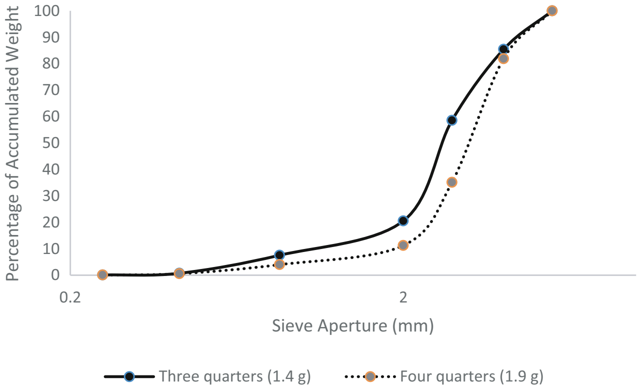

**FIGURE 1** The effect of the different bolus sizes on the cumulative frequency curve exemplified for a 9-year-old girl. This girl's MPS ($X_{50}$, 2.69 mm) when chewing on three quarters is very close to the sample's mean value (2.56 mm); BPD is 2.83. Her MPS ($X_{50}$) was 3.16 mm when chewing on four quarters and her BPD was 3.82. The horizontal axis corresponds to the logarithm of the sieve aperture (mm). The curve for the larger bolus size is shifted to the right toward larger sieve apertures than for the smaller bolus size

## 4 | DISCUSSION

The results of this study show that the bolus size influences intraoral food breakdown in children, analogous to what occurs in adults. The smaller $X_{50}$ at ST and the larger number of cycles/g indicate more intraoral breakdown with a smaller bolus.

Although we only swallow digestible foods after chewing, studies on masticatory function also commonly use artificial test foods (Bonnet, Batisse, Peyron, Nicolas, & Hennequin, 2019; Gonçalves et al., 2021) to eliminate the influence of variability in initial size, hardness, and water content of natural foods. The silicone rubber Optosil, a dental impression material, is representative of selection and breakage processes of natural foods such as nuts or raw carrot, that are hard and form a loose aggregation of particles during chewing. In addition to providing relevant insight into the selection process of food comminution during natural chewing (van der Glas et al., 2018), sensory testing of Optosil tablets and natural foods reported its similarity to carrot (Portilla-Juarez, 2015). Different variants of Optosil have been used in chewing studies with artificial test foods. The force, percentage compression and the work at fracture for Optosil Comfort are larger than for other versions (van der Glas, Al-Ibrahim, & Lyons, 2012).

The required bite force, which is approximately proportional to the number of particles selected, is not a limiting factor with respect to the MOF in young adults when using Optosil version 1980 (Liu et al., 2019, 2020). The reduction in MP of these adults with increasing initial numbers of particles (2, 4, or 9 9.6 mm half-cubes with a volume of 0.44 $\text{cm}^3$ each) at various numbers of chews is therefore due to increased saturation of the available breakage sites on the teeth. The decrease in $X_{50}$ with an increase of offered quarters of an Optosil Comfort tablet (volume of 0.39 $\text{cm}^3$ each, 10 mm sieve size) from three to four pieces in the children in the present study, is primarily also due to an increase of saturation of the breakage sites. The increase in saturation will even be more pronounced in children than in adults due to a smaller size of their jaws and teeth when using a

**TABLE 3** Regression analysis of linear relationships between MPS 3/4, MPS 4/4, MOF, cycles ST 3/4, cycles ST 4/4, cycles/g 3/4, cycles/g 4/4 ($n = 89$)

| Dependent variable | Independent variable | Gradient | Intercept | $R^2$ | Pearson's *r* | *p* Value |
|---|---|---|---|---|---|---|
| MPS 4/4 | MPS 3/4 | 0.689 | 1.032 | .645 | .803 | <.001 |
| MPS 3/4 | MOF | −0.002 | 3.515 | .085 | .291 | =.006 |
| MPS 4/4 | MOF | −0.002 | 3.517 | .066 | .256 | =.016 |
| MPS 3/4 | Cycles ST 3/4 | −0.011 | 2.997 | .044 | .209 | =.049 |
| MPS 4/4 | Cycles ST 4/4 | −0.010 | 3.219 | .056 | .237 | =.026 |
| Cycles/g 4/4 | Cycles/g 3/4 | 0.675 | 3.549 | .647 | .805 | <.001 |

*Note:* $R^2$ fraction of the variance of the dependent variable explained by the independent variable. MPS, median particle size ($X_{50}$); MOF, maximum occlusal force; ST, swallowing threshold; three quarters (1.4 g) are expressed as 3/4 and four quarters (1.9 g) as 4/4.

similar particle size. The force needed to break harder and more elastic particles made of Optosil Comfort is greater than for ones of Optosil version 1980 (about 90 vs. 75 N yield force per particle). Children with a MOF of less than 180 N can select and further break only one particle out of three to four initial Optosil Comfort quarters. Both factors, however, saturation of breakage sites and force limitation will yield a reduced rate of particle size reduction when chewing four rather than three initially large particles. The strong correlation (Pearson's $r = .803$) between $X_{50}$ when chewing the two different bolus sizes implies that a good chewer chews better with any bolus size than a bad chewer. $X_{50}$ with three quarters explains 65% of the variance of $X_{50}$ with four quarters. The bolus sizes tested in the current study are within normal limits for children (Wintergerst, Garza-Ballesteros, & Garnica-Palazuelos, 2016) and based on the results of this study we recommend three quarters should continue to be used as the size of the artificial test food Optosil to evaluate food breakdown in children.

We did not find any studies comparing food breakdown at ST with different bolus sizes in children. In adults and when using hard-baked soya beans as a natural test food, Jiffry (1983) found that larger particle sizes occurred at ST with greater mouthfuls and Lucas and Luke (1984) found that $X_{50}$ was larger at ST with 5 and 12 g than with 1 g of peanuts. Thus, the effect of a larger bolus size on the particle size at ST in adults also applies to 8–10-year-old children. The difference in $X_{50}$ when chewing on two different bolus sizes found in the current study is smaller than the 16% difference found in young adults when using the same test food (albeit a different version) and bolus sizes although they tested $X_{50}$ after 20 chewing cycles (Buschang et al., 1997) and larger differences are expected with fewer cycles.

In the current study, the median number of chewing cycles required to reach ST increased from 37.6 with three quarters to 39.8 with four quarters; this difference was small, although statistically significant. Since the weight (volume) of a chewing sample increased 33% by increasing the number of quarters from 3 to 4, while the number of chewing cycles until ST increased only 9%, the number of cycles per gram of the test food decreased. Our finding of more chewing cycles but fewer cycles per gram of test food using a larger bolus size are consistent with reports in adults using softer natural foods, that is, peanuts (Lucas & Luke, 1984) and cooked rice and fish sausage (Goto et al., 2015).

The increase in the number of cycles with a larger bolus content is in all studies never sufficiently large to achieve the same breakdown as with the smaller bolus. While $X_{50}$ in the present study averaged 2.56 mm for chewing samples of three Optosil Comfort quarters, $X_{50}$ was significantly larger at 2.80 mm for four quarters. The difference in $X_{50}$ value suggests that a subject's inclination to swallow is not related to a specific $X_{50}$ value when using this artificial test food. The range in the size of the particles from each individual's chewing sequence is large (Grundy et al., 2015) as exemplified for one child in Figure 1.

Optosil is a hydrophobic, chemically inert silicone rubber, which does not soften with saliva during chewing and forms a loose aggregation of particles. The coherence and adhesion of a food bolus will play a minor role for the aggregation of Optosil particles in saliva, compared to a sticky natural food whose particle texture is altered by saliva during chewing. ST for Optosil may therefore be primarily related to the production of a sufficient amount of saliva for swallowing, during a number of chewing cycles that hardly depend on the number of initial particles used in the present study. The chewing time before the first swallow of Japanese steamed rice is inversely related with stimulated saliva flow rate in individual subjects (Pearson's $r = .48$) but not to MOF or maximal tongue pressure, emphasizing the importance of saliva flow in swallowing (Kochi et al., 2021). Future research that includes a determination of saliva flow rate is needed to further investigate ST of Optosil.

Sequence duration was longer when chewing the larger bolus size due to the approximately 2-cycle difference between bolus sizes in addition to the finding that each individual's chewing cycle was on average 5% longer with the larger bolus size. A 5% increase in cycle duration was also reported for adults chewing gum between a 1.9 and a 3.7 bolus size (Shiga, Stohler, & Kobayashi, 2001). The longer chewing cycle duration found here could be explained by more difficulty for the tongue and cheeks to control a larger amount of food. It would be interesting to explore if the longer duration would be attributed to a longer opening, closing or occlusal phase.

MOF is inversely related to $X_{50}$ and explains about 11% (Lepley et al., 2011) to almost half the variance (Fontijn-Tekamp et al., 2000) of MP in adults and about 20% of the variance after 20 cycles and at ST in children (Arias-Marquez, 2015). In the current study, MOF explained less than 9% of $X_{50}$ and explains more variance with the smaller bolus than with the larger bolus. The correlation between MOF and $X_{50}$ in the current study was lower (Pearson's $r = 0.256$–0.291) than that found in a previous study ($r = -.435$) with three quarters of the test food, but that study included children from an urban and a rural community with large differences in occlusal force and $X_{50}$ (Arias-Marquez, 2015). MOF also hardly influenced the degree of fragmentation of Optosil 9.6 mm half-cubes (version 1980) at the first chewing cycle or chewing efficiency (the number of chews required to half the initial particle size) in young adults (Liu et al., 2020). Liu et al. have suggested that the weakness of relationships between MOF and variables of chewing ability is due to a molar bite force acting at a suprathreshold level rather than the maximal level.

Since MOF has been associated with food breakdown and body size (Julien et al., 1996) we compared MOF between normal weight, overweight or obese children, but found no significant differences. Our finding that there are no significant MOF differences may be related to homogeneity of the subject groups regarding age and jaw size. The subjects in the study of Julien et al. (1996) were heterogenous in this regard. Our MOF result is consistent with other studies in children. Pedroni-Pereira et al. (2016) found no statistically significant differences in MOF between normal weight or overweight/obese adolescents. BMI only explained 1.3% of the variance in MOF in adolescents (Varga et al., 2011) and no significant correlation was found between MOF and body mass index or between body mass index and MP with an artificial test food in 3–5-year-old children (Gavião, Raymundo, & Rentes, 2007). Our finding of no difference in MOF based on their nutritional status may partly contribute to our finding of no differences in $X_{50}$ between the three groups based on nutritional status. de Morais Tureli, de Souza Barbosa, and Gavião (2010) found a smaller $X_{50}$ in normal weight children than in overweight/obese children using Optocal after 20 chewing cycles; they suggested that the better MP of normal weight children might be related to stronger jaw muscles due to a diet history of harder foods whereas overweight/obese children might have weaker jaw muscles due to a preference of diets with softer foods. MOF measurements to support this suggestion are regrettably lacking. Sex also did not affect $X_{50}$, in the present study, similar to what others have reported for this age group (Barrera et al., 2011; Toro et al., 2006).

As previously mentioned, the findings of this study in children as in previous studies in adults show that the greater the bolus content, the less particle size is reduced at ST and fewer chewing cycles are performed per gram of test food. Conversely, the particle size at ST is smaller with a smaller bolus content. Thus, smaller particles swallowed after chewing a smaller food input would provide a high surface area/volume ratio. Choosing a small bolus content thus seems beneficial in light of the fact that chewing is the first step of the digestive process that affects bioaccessibility. Mechanical breakdown of food during intraoral processing contributes to the accessibility of food fragments to digestive enzymes leading to an increase in digestion efficiency and the kinetics of gastrointestinal utilization of nutrients (Chen, Capuano, & Stieger, 2021); although particle size is further reduced in the stomach (Kong & Singh, 2008). The finding of a smaller value of the ratio of chews/g of food, following the chewing until ST of a larger food input, reflects a delivery rate of each gram of food with its potential metabolic energy to the gastrointestinal tract, which is greater than the rate of a smaller food input, within a chewing sequence (cf. discussion in Lucas & Luke, 1984).

Chewing a small food input each time may help prevent overeating and obesity and will cause more flavor release through better particle size reduction, creating more surface area per volume unit. However, before a chewing result in a ST test can be appropriately linked to gastrointestinal digestion, the following issues must be considered. First, the increase in $X_{50}$ between particle samples is small in the present study, that is, only 9% with respect to $X_{50}$ of the smaller chewing sample. The clinical significance of this limited change in particle size and surface area per volume unit is unclear. Would this small difference if long-lasting affect gastric function? Second, a subject is only inclined to be able to swallow a food bolus at ST but does not swallow it. Although swallowed Optosil particles would be excreted harmlessly, subjects are explicitly instructed not to swallow Optosil. Regardless of the use of an artificial test food or a digestible food, a subject's ST will depend on his/her interpretation of an instruction to stop chewing when "ready to swallow the food bolus." When "ready to swallow" includes an inclination to swallow the entire bolus, ST might be affected by a subject's ability to suppress an initial inclination to swallow part of the bolus. A major limitation of the ST test used in the present study as in others is that all swallowing is assumed to be a single event at the end of a chewing sequence. In contrast, in a natural context, chewing is regularly interrupted (Gerstner & Cianfarani, 1998; Po et al., 2011), in part for swallowing part of a food bolus in between. In the study of Gerstner and Cianfarani (1998), 67% of the sampled chewing bursts lasted ≤4 s and consisted of 1–4 chews, and 33% had a duration of >4 s, with the longest burst consisting of 22 consecutive chews. Videofluorography shows that swallowing during a chewing sequence occurs on average 2.7 times (*SD* 0.9) for a soft bolus of white rice and 2.3 times (*SD* 0.8) for Japanese udon noodles (Iida, Katsumata, & Fujishita, 2011). Future research is needed on the effects of interposed swallowing on the entire digestion process using a different paradigm than that of a traditional simplified test on ST.

## 5 | CONCLUSION

In 8–10-year-old children a larger bolus size with more particles of the test food increases the MPS, $X_{50}$, at the ST. The number of chews up to the "ready to swallow the food bolus" stage increases with more particles, and the ratio of chews/g food decreases. Despite more chews until ST, the extra chewing does not compensate for the increase in $X_{50}$ due to more particles. MOF is similar between normal weight, overweight or obese children. MOF is only weakly related to $X_{50}$ at ST, suggesting that a molar bite force involved in the neuromuscular control for generating an appropriate timing, direction and range of action operates at a suprathreshold level. Due to a smaller $X_{50}$ at ST, choosing a small bolus content appears to be beneficial for bioaccessibility of food.

The findings of this study raise questions on the possible health and quality of life effects of chewing large bolus sizes in children. Unfortunately, there is scarce research on intraoral processing and the consequences of incomplete breakdown of food in children that could affect their health. Further research in children with crosstalk between different disciplines is needed to fully understand how (a) intraoral processing adapts to changes in bolus size, (b) if swallowing large particles affects their gastrointestinal digestion, and (c) if there is a relation between nutritional status and bite size or intraoral processing.

## ACKNOWLEDGEMENTS

This work was supported by a grant (IN-231320) from Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT), Universidad Nacional Autónoma de México. The authors would like to acknowledge the authorities, parents, and teachers of the two schools that participated, and Roberto Samuel Gómez-Zúñiga would like to thank CONACyT for the scholarship during his Master program.

## AUTHOR CONTRIBUTIONS

**Ana Wintergerst:** Conceptualization (lead); data curation (supporting); formal analysis (lead); funding acquisition (lead); writing – original draft (lead); writing – review and editing (lead). **Roberto Samuel Gómez-Zúñiga:** Conceptualization (supporting); data curation (lead); formal analysis (supporting); writing – original draft (supporting); writing – review and editing (supporting).

## ETHICAL STATEMENTS

Conflict of Interest: The authors declare that they do not have any conflict of statement.

Ethical Review: This study was reviewed and approved by the Ethics Committee of the School of Dentistry (CIE/0810/11/2018).

Informed Consent: Written informed consent was obtained from all the parents of the participants prior to the study; children gave their written and verbal assent.

## DATA AVAILABILITY STATEMENT

Data may be accessible upon a reasonable request.

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**How to cite this article:** Wintergerst, A., & Gómez-Zúñiga, R. S. (2022). The effect of bolus size on masticatory parameters at swallowing threshold in children using a hard, solid, artificial test food. *Journal of Texture Studies*, *53*(3), 374–382. https://doi.org/10.1111/jtxs.12671