Odontology (2001) 89:49–53

ORIGINAL ARTICLE

Hiroshi Shiga · Christian S. Stohler · Yoshinori Kobayashi

The effect of bolus size on the chewing cycle in humans

Received: October 10, 2000 / Accepted: July 16, 2001

Abstract No general agreement exists regarding the effect that bolus size has on masticatory movement, probably because both the size and texture of food change during mastication. In this experiment, in order to clarify the effect of bolus size on masticatory movement, a food that does not change in size and texture – chewing gum – was chosen, and the relationship between bolus size and the chewing cycle was analyzed. Ten healthy subjects in their twenties were asked to chew pieces of softened chewing gum of four different sizes. For ten cycles, beginning with the fifth cycle of mastication, gape and masticatory width were calculated for the spatial parameter of the chewing cycle, and cycle time was calculated as the temporal parameter. The relationship between these parameters and the bolus size was investigated. As the bolus size increased, the spatial and temporal parameters increased. In addition, there was a positive correlation between the bolus size and each parameter. The influence of the bolus size was as follows: gape, $r = 0.91$; masticatory width, $r = 0.79$; and cycle time, $r = 0.74$ (all, $P < 0.001$). From these results it was concluded that the shape of the chewing cycle was altered by the size of the food bolus, and that the changes in sensory input from the peripheries greatly affected the masticatory movement.

Key words Chewing movement · Bolus size · Gape · Masticatory width · Cycle time

H. Shiga (✉) · Y. Kobayashi
Department of Removable Prosthodontics, The Nippon Dental University School of Dentistry at Tokyo, 2-3-16 Fujimi, Chiyoda-ku, Tokyo 102-8158, Japan
Tel. +81-3-3261-5729; Fax: +81-3-3261-8464
e-mail: h-shiga@tokyo.ndu.ac.jp

C.S. Stohler
Department of Biologic and Materials Sciences, School of Dentistry, University of Michigan, Ann Arbor, MI, USA

Introduction

Early reports have suggested that each human subject has a characteristic masticatory behavior, and that this pattern of chewing is influenced by the nature of the food.[1] Similar observations were made in animals. In the monkey, the duration of the chewing cycle and the magnitude of the lateral excursion is smaller with softer food.[2] In the cat, in experiments using liver of three different consistencies and three bolus sizes, cycle duration and gape increased with bolus size, and to a lesser degree, with the hardness of the food.[3] As far as the human is concerned, bolus size and food consistency were reported to influence the gape in a similar manner.[4–6] However, Plesh et al.[7] were unable to observe an influence of bolus consistency on gape, and Pröschel and Hofmann[8] reported a negative influence of consistency on gape. The magnitude of the lateral excursion of the chewing cycle has been reported to increase with bolus size,[4] and with a harder food consistency.[6,8] On the other hand, Lucas et al.[5] were unable to find such a relationship. The duration of the chewing cycle was found to increase with increased hardness of the food;[7,8] no statistically significant difference was reported for bolus size[4,5] or consistency.[7] There are also reports indicating changes of the spatial and temporal characteristics of the chewing cycle within a masticatory sequence. A decrease in vertical gape with increased comminution of food was noted.[9,10] Observations of both a decrease in cycle duration and vertical gape with time within a masticatory sequence were found in humans,[11] while a decrease in cycle duration with time was found in the monkey.[2] Last but not least, the masticatory movement was reported to be disturbed at the beginning of the masticatory sequence.[12,13] In summary, these observations demonstrate that bolus size and food consistency can influence cycle duration, vertical gape, and lateral mandibular excursion. Because food changes its textural properties within a masticatory sequence, these intrinsic changes could, potentially, affect the results and explain some of the differences found in the literature.

Therefore, we wanted to examine the effect of bolus size on the spatial and temporal parameters of the human chewing cycle. For our investigations, the experiments involved the chewing of gum. Gum was selected because, after the initial softening, it does not change its properties within a chewing sequence. This research was aimed at studying the effect of bolus size on vertical gape, masticatory width, and cycle time in mastication. We were also interested in examining whether or not the spatial and temporal variability from cycle to cycle within a chewing sequence was affected by bolus size.

Materials and methods

Our subjects were ten healthy individuals, five men and five women, aged between 23 and 28 years (average, 25.2 years), each of whom had a full complement of teeth, excluding third molars. All subjects were free of facial pain and had no complaints about their bite. Informed consent forms were obtained, and the general nature of the study was explained to the subjects, after which they signed the forms. For the study, the subjects were seated comfortably in chairs so that their Frankfurt horizontal plane was parallel to the floor. They were requested to chew in their habitual manner. One to four types of mildly flavored gum (Trident R; Warner-Lambert, Parsippany, NJ, USA) with bolus sizes of $0.9\,cm^3$, $1.9\,cm^3$, $2.8\,cm^3$, and $3.7\,cm^3$ were selected. Before the mastication of the four types of gum was recorded, the subjects were allowed to get used to the bolus size by softening the chewing gum adequately. Therefore the order of mastication was not random, but, rather, was done from the smallest bolus size. It was also verified that all subjects were able to unconsciously chew the test bolus without any difficultly. Mandibular movement was characterized by incisal point displacement in a vertical, latero-lateral, and antero-posterior direction, using the K6I measuring system (Myotronics, Seattle, WA, USA).

After the separation of the chewing sequence into individual chewing cycles, ten consecutive cycles from the fifth cycle were subjected to further processing. The separation of a chewing sequence into individual cycles was accomplished using software routine. First, an initial threshold value was established, at 2mm below the highest point of masticatory movement, and masticatory cycles were separated into individual cycles. Next, a second threshold value was obtained, as the average of all the vertical components above the initial threshold value. Then the average and the standard deviation of all vertical components above the second threshold value was obtained. The final threshold value was the sum of the latter two values. From the final threshold value, the starting points for opening phase, closing phase, and occluding phase were automatically determined (Fig. 1). The cycle time was defined as the duration from the onset of the chewing cycle to the onset of the next chewing cycle. The chewing envelope was divided vertically into ten equally spaced sections, and the crossing of the movement path at each sectional crossing was determined. The gape was defined as the vertical distance from intercuspation to maximum jaw opening, and the masticatory width was defined as the average width from the first to the ninth level (Fig. 2). The gape and the masticatory width were used as the spatial parameter, and the cycle time was used as the temporal parameter. For the data of chewing four different types of chewing gum, the spatial and temporal parameters were calculated for the ten cycles beginning with the fifth cycle of mastication. Next, the average for the 40 cycles was obtained and the value of each cycle was standardized so that the average would be 1. For these parameters of the masticatory cycle, the average and

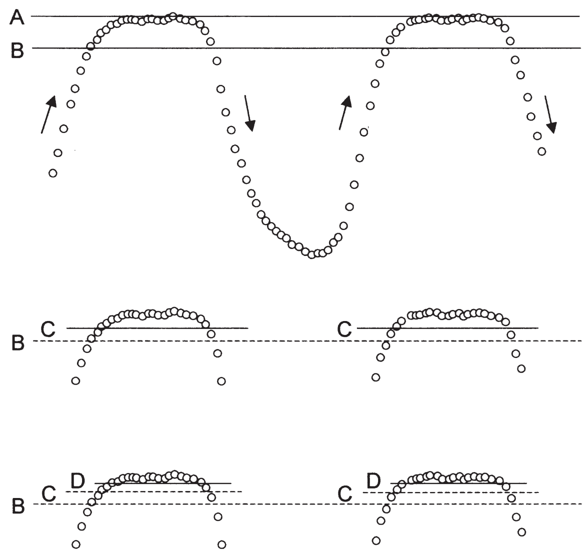

Fig. 1. Recognition of opening, closing, and occluding phases. *Circles*, Vertical component; *A*, highest line of masticatory movement; *B*, initial threshold; *C*, second threshold; *D*, third threshold

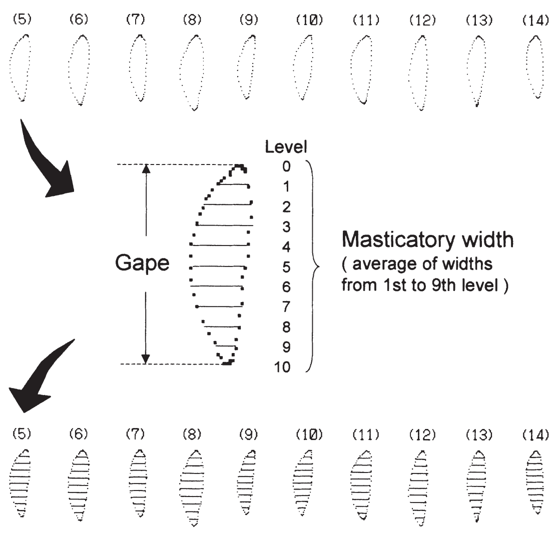

Fig. 2. Definitions of gape and masticatory width

Table 1. Average values (and SDs) of spatial and temporal parameters

Bolus size	$0.9\,cm^3$	$1.9\,cm^3$	$2.8\,cm^3$	$3.7\,cm^3$
Gape	0.87 (0.04)	0.98 (0.03)	1.04 (0.03)	1.11 (0.04)
Masticatory width	0.86 (0.09)	0.96 (0.09)	1.05 (0.07)	1.14 (0.09)
Cycle time	0.97 (0.02)	0.98 (0.02)	1.00 (0.01)	1.03 (0.02)

Table 2. Results of paired *t*-test (*t*-value)

Bolus size groups	Gape	Masticatory width	Cycle time
$0.9\,cm^3$ vs $1.9\,cm^3$	4.62**	2.41*	1.84
$1.9\,cm^3$ vs $2.8\,cm^3$	5.31**	2.70*	2.88*
$2.8\,cm^3$ vs $3.7\,cm^3$	4.01**	2.74*	3.15*

* $P < 0.05$; ** $P < 0.01$

the coefficient of variation (CV) were calculated, using the data of the ten cycles from the fifth cycle of mastication. The average value of each parameter for the four bolus sizes was compared, using repeated measures analysis of variance (ANOVA). If the repeated measures ANOVA showed a statistically significant effect, follow-up comparisons were carried out with the paired *t*-test. The relationship between these parameters and the size of the food bolus was investigated using Pearson's correlation coefficient test. In order to examine whether or not a larger bolus size led to greater variation in the chewing parameters, the CVs of the chewing parameters for the four bolus sizes were compared using Friedman's test.

Results

The average values for gape, masticatory width, and cycle time for 40 cycles were 21.1 mm (SD, 1.9 mm), 2.7 mm (SD, 1.1 mm), and 493.1 ms (SD, 48.3 ms) respectively.

Both the spatial (gape and masticatory width) and temporal (cycle time) parameters of the human chewing cycle were affected by the volume of the bolus ($P < 0.001$).

Spatial and temporal parameters of the chewing cycle

Average values for the spatial and temporal parameters are shown in Table 1. Of all the measured parameters of the chewing cycle, the effect of bolus size on gape was most obvious. The effect of bolus size on the masticatory width of the chewing cycle was also obvious. The gape and masticatory width increased to a significant degree with increasing volume of the bolus (Table 2). The cycle time was moderately influenced by the increase in bolus size. When bolus sizes of $0.9\,cm^3$ and $1.9\,cm^3$ were compared, the cycle time was not significantly different. However, this was no longer the case when a bolus size of $1.9\,cm^3$ was compared with $2.8\,cm^3$, or that of $2.8\,cm^3$ was compared with $3.7\,cm^3$ (Table 2).

Relationship between bolus size and chewing parameters

As the bolus size increased, the spatial and temporal parameters also increased, and there was a positive correlation between the bolus size and each parameter (Fig. 3).

Variability of chewing parameters from cycle to cycle

There were no significant differences in the variability of the spatial or temporal parameters from cycle to cycle, that could be related to bolus size ($P > 0.05$). The CV values were 6% to 7% for gape, 19% to 21% for masticatory width, and 4.5% to 4.9% for cycle time.

Discussion

Because food changes its physical properties with increased comminution,[14] we chose chewing gum for our experiments. We assumed that some of the inconsistencies in the literature could be explained by the intrinsic changes of bolus size and/or bolus consistency that occur within a sampling period. Of all the parameters studied, the effect of bolus size on gape was most significant. This finding is consistent with earlier findings in both cats[3] and humans[4,5] (Table 3). With food, rather than gum, gape decreased within a chewing sequence,[9,10] most notably within the first few cycles.[11] Based upon the literature and our findings, it is safe to conclude that the bolus size has a direct effect on gape. An effect of bolus size on masticatory width was also noted in our data set. However, the effect of bolus size on masticatory width was not as pronounced as its effect on the gape. This observation is in agreement with the findings of Mizumori et al.,[4] who used radish as the test food. However, Lucas et al.,[5] who used peanuts, found no effect of bolus size on masticatory width (Table 3). To explain this difference, we considered two possibilities, arising from the difference in the bolus. One is that, in our experiment, we used chewing gum, the hardness of which did not change during mastication, whereas Lucas et al.[5] used peanuts, which become softer and smaller during mastication. It has been reported that the lateral movement decreased as food became softer.[1] Thus, it is highly probable that, as with the gape and cycle time, the changes in the consistency of the food that occurred during mastication affected their results. The other possible explanation is a difference in the consistency of the bolus. Lucas et al.[5] used peanuts, which are hard and breakable and require much vertical movement. In our study, the use

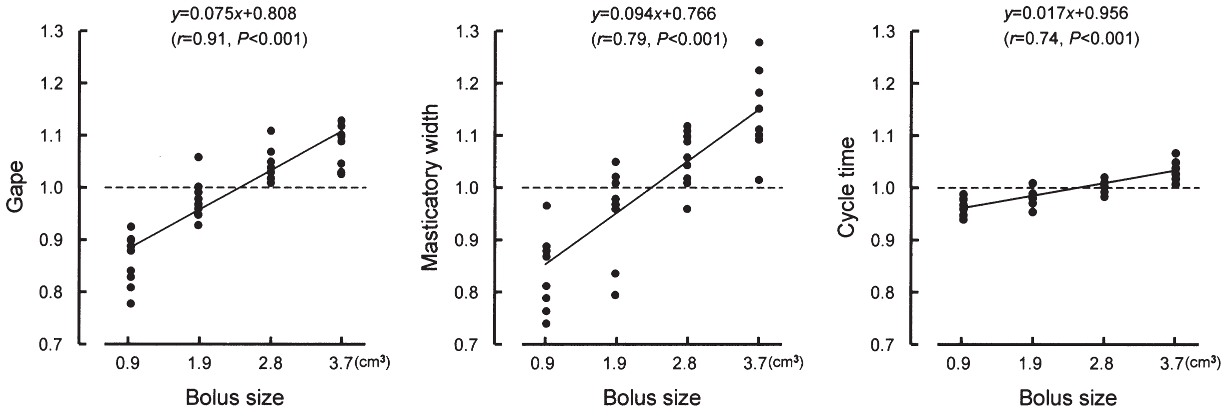

Fig. 3. Relationship between bolus size and chewing parameters

Table 3. Relationship between bolus size and gape, masticatory width, and cycle time as reported in the literature

	Bolus	Gape	Masticatory width	Cycle time
Thexton et al. (cats)[3]	Liver	Increase	Not available	Increase
Mizumori et al. (humans)[4]	Radish	Increase	Increase	NS
Lucas (humans)[5]	Peanuts	Increase	NS	NS
Present study (humans)	Gum	Increase	Increase	Increase

Increase, Increase with increased bolus size; NS, no significant influence

of chewing gum, which is soft and viscous, necessitated lateral movements that could have been more responsive to the change in bolus size.

Least clear, but still statistically significant, was the influence of bolus size on the cycle time. It has been suggested that, as the size of the food bolus increased, resistance also increased and the velocity decreased.[15] Therefore, it is possible that the reason for the increase in cycle time as the size of food increased could be that the increase in resistance reduced the masticatory velocity, and, as a result, cycle time was prolonged. The influence of bolus size on cycle time has also been observed when liver was fed to cats;[3] however, studies in humans did not find such a relationship.[4,5] We concluded that bolus characteristics, such as consistency and stickiness, were likely to influence cycle time. This hypothesis was partially supported by the finding that, as the food became harder, the cycle time increased.[7,8] However, the change in cycle time with the size of the food bolus was 0.97 to 1.03, with boluses of 0.9 cm^3 to 3.7 cm^3, which was relatively small when compared with the change of 0.87 to 1.11 for gape and 0.86 to 1.14 for masticatory width. This was probably because masticatory rhythm was basically determined by the pattern generator of the brain stem,[16] so that the temporal characteristics of chewing may be not as susceptible to peripheral feedback as the spatial characteristics.

Our findings that bolus size did not influence either the spatial or temporal cycle-to-cycle variation of cycle parameters are new. This was surprising to us, because we expected that a larger bolus would likely call for greater cycle-to-cycle variation of gape, masticatory width, and cycle time. However, this was not the case for any of the parameters. Therefore, it could be concluded that the changes from cycle to cycle did not affect the results of this experiment.

As mentioned previously, it has been reported that the size and the hardness of food change during mastication,[14] that masticatory movement was disturbed at the beginning of a continuous mastication,[12,13] and that there were individual variations in the parameters that quantitatively manifest masticatory cycles, such as gape, masticatory width, and cycle time.[7] These individual variations are actually the main sources of the ambiguity that exists in comparing different types of food. Therefore, in this experiment, in order to eliminate these sources of ambiguity, we chose as the test bolus a softened chewing gum that did not change much in either size or hardness during mastication. In addition, the first few cycles of mastication, in which the subjects tended to be conscious of the action, were eliminated from the analysis, and the ten cycles beginning with the fifth cycle were selected. Also, in order to eliminate individual variations, each parameter was standardized. As it is known that, when a change in size from one bolus to the next is large, this may elicit a voluntary response in subjects, which may, in turn, cause disturbance in the rhythmical masticatory movement. Thus, the test boluses we used were adequately softened and tested in order of size, beginning with the smallest bolus, so as to get the subjects accustomed to the bolus size. By thus paying attention to the conditions of the experiment, we were able to observe that there was a significant relationship between the bolus size and each parameter of the chewing cycle. From these results it was concluded that bolus size positively affected the spatial and temporal parameters of mastication.

References

1. Ahlgren J. Mechanism of mastication: a quantitative cinematographic and electromyographic study of masticatory movements in children, with special reference to occlusion of the teeth. Acta Odontol Scand 1966;24 (Suppl 44):1–109.
2. Luschei ES, Goodwin GM. Patterns of mandibular movement and jaw muscles activity during mastication in the monkey. J Neurophysiol 1974;37:954–66.
3. Thexton AJ, Hiiemae KM, Crompton AW. Food consistency and bite size as regulators of jaw movement during feeding in the cat. J Neurophysiol 1980;44:456–74.
4. Mizumori T, Kuwahara T, Nishio K, Miyauchi S, Maruyama T. Clinical studies on chewing movements, effects of foods size and hardness. J Jpn Prosthodont Soc 1985;29:1062–9.
5. Lucas PW, Ow RKK, Ritchie GM, Chew CL, Keng SB. Relationship between jaw movement and food breakdown in human mastication. J Dent Res 1986;65:400–4.
6. Higashi K. A clinical study on the relationship between chewing movements and masticatory muscle activities. J Osaka Univ Dent Soc 1989;34:26–63.
7. Plesh O, Bishop B, McCall W. Effect of gum hardness on chewing pattern. Exp Neurol 1986;92:502–12.
8. Pröschel P, Hofmann M. Frontal chewing patterns of the incisor point and their dependence on resistance of food and type of occlusion. J Prosthet Dent 1988;59:617–24.
9. Wickwire NA, Gibbs CH, Jacobson AP, Lundeen HC. Chewing patterns in normal children. Angle Orthod 1981;51:48–60.
10. Schindler HJ, Stengel E, Spiess WEL. Feedback control during mastication of solid food textures – a clinical-experimental study. J Prosthet Dent 1998;80:330–6.
11. Jemt T, Karlsson S, Hedegård B. Mandibular movements of young adults recorded by intraorally placed light-emitting diodes. J Prosthet Dent 1979;42:669–73.
12. Kawamura Y, Kishi K, Nobuhara M, Fujimoto J. Studies on masticatory function 1. An electromyographic analysis of the chewing pattern of the normal occlusion and malocclusion. Med J Osaka Univ 1957;8:229–40.
13. Inaba J, Shiga H, Kobayashi Y. Peripheral feedback adjustment in chewing various types of food. J Dent Res 2000;79:1238.
14. Gibbs CH, Lundeen HC, Mahan PE, Fujimoto J. Chewing movements in relation to border movements at the first molar. J Prosthet Dent 1981;46:308–22.
15. Van Der Bilt A, Van Der Glas HW, Olthoff LW, Bosman F. The effect of particle size reduction on the jaw gape in human mastication. J Dent Res 1991;70:931–7.
16. Lund JP. Mastication and its control by the brain stem. Crit Rev Oral Biol Med 1991;2:33–64.