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Original article

Differences in comminution progress during mastication in healthy dentate and denture-wearing elderly people

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ABSTRACT

Purpose: This study aimed to investigate the effect of removable denture prostheses on the comminution progress in elderly people.

Methods: Twenty-two denture wearers of Eichner's classification B and C (75.1 ± 5.3 years old) and 20 young fully dentate subjects (27.6 ± 1.9 years old) participated in the masticatory examination, which used a combined test food from 5 daily food materials. Full masticatory cycles lasting until subjects needed to swallow and the half number of the cycles were adopted as masticatory conditions. Digital images of food particles under wet conditions were obtained for each bolus, and particles were analyzed by calculating the homogeneity and particle size indices.

Results: The characteristic properties of the food particles were observed using a homogeneity index in the elderly denture group for half masticatory strokes. Their homogeneity index was significantly higher than that of the young dentate group. By contrast, no significant difference was observed in the indices for particles immediately before swallowing between two groups.

Conclusions: The comminuted particle size before swallowing in healthy denture wearers was not significantly different from that in the natural dentate group. The comminution of the first-half process in denture wearers was typical and could be one possible focus for meal property specifications in future studies.

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1. Introduction

The quality of the diet is known to greatly affect quality of life (QOL) of elderly people [1]. With regard to smooth and safe food intake, accurate assessment of the remaining masticatory function plays an important role in evaluating QOL of dysphagia patients [2,3].

The number of missing teeth increases with aging, and the mastication function is supported by wearing denture prostheses. The Survey of Dental Diseases [4] showed that more than half of elderly people wear removable dentures in Japan. Therefore, wearing dentures is an important factor in the diet of elderly people. Revealing the detailed progression of the mastication process in denture wearers can help address the masticatory problems that elderly people are facing.

Various studies have been reported on the characteristics of mastication in denture wearers. Wayler et al. [5] reported that denture wearers make a much coarser bolus than dentate subjects

by analyzing the particle size distribution of the food bolus immediately before swallowing. In addition, several studies that used particle distribution reported that the masticatory efficiency of full denture wearers was decreased by more than 50% compared with subjects with intact dentition [6–8]. Ikebe et al. reported that a masticatory performance using gummy jelly was 81% and 50% in elderly subjects from Eichner's Index group B and C compared to that of Eichner's Index group A, respectively [9]. However, apart from these reports on the overall chewing efficiency or chewing performance, there is limited knowledge of the detailed process of mastication progression. The number of posterior teeth is a key factor in predicting chewing efficiency [10].

As mastication is a complex process, masticatory function has been evaluated from various aspects, including pulverization, biting or mixing. Sieving of fragmented particles after chewing natural or artificial food, such as peanuts, almond, carrots and dental impression material, is a reliable method to quantify masticatory performance [11–14]. The mixing ability has been evaluated using colored chewing gum or paraffin wax, and the concentration of dissolved glucose obtained from gummy jelly mastication represents another methodology [15–17]. Considering the complicity of mastication process, it is reasonable to evaluate

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the segmentalized property of the phenomenon utilizing a simplified test food material and methodology. These modalities should be selected depending on the purpose of the experimental analysis. When evaluation of the ability of elderly people to masticate and intake daily foodstuffs is the main point of clinical interest, evaluation of the mastication process using daily foodstuffs of daily cuisine would represent a direct modality. Sugimoto et al. reported a method to quantitatively evaluate the comminution of mixed test foods; the method simulated daily meals and used particle size analysis in a food bolus [18]. As their method is able to evaluate most types of food, it is applicable for the evaluation of the daily food mastication ability. In addition, revealing the precise characteristics of mastication processes using daily food may contribute to improving denture structure designs in the future.

This study aimed to reveal and compare the detailed progression of the masticatory process in the young dentate group and denture wearers using particle size analysis. The bolus particle distribution was analyzed based on two aspects, particle size and homogeneity. The research hypothesis was that there is no difference in the progression of comminution between the young dentate group and denture-wearing elderly people.

2. Materials and methods

2.1. Subject

Two subject groups were assigned in this study. One group was the young dentate group (Y-group), which included students and faculty of Okayama University Dental School. The other group was the denture wearer group (D-group), which included patients from Okayama University Department of Prosthodontics.

The Y-group consisted of 20 young dentate subjects (10 males and 10 females, mean age 27.6 ± 1.9 years). The D-group consisted of 22 elderly denture-wearing subjects (13 males and 9 females, mean age 75.1 ± 5.3 years). The inclusion criteria for the Y-group were (i) healthy adult 20–50 years old, (ii) with full natural dentition (except for the third molars), (iii) no subjective symptoms during deglutition of daily food intake, and (iv) each premolar and molar makes occlusal contact with opposing tooth. The inclusion criteria for D-group were (i) healthy people older than 65 years old, (ii) wearing removable dentures for Eichner's index [19] group B3, B4 or C, and (iii) no subjective symptom during deglutition of daily food intake and swallowing. The exclusion criteria for the D-group were (i) edentulous, (ii) moderate to severe periodontitis on residual teeth. Periodontal status was evaluated using the Community Periodontal Index (CPI) [20], and subjects with CPI Code ≥ 3 were excluded from this study. All the removable dentures were fabricated in the clinical division of removable prosthodontics at Okayama University Hospital. No unfavorable complaints regarding the prosthesis were reported when subjects were enrolled in this study. The exclusion criteria were (i) those who were likely to have allergic symptoms from the test food and (ii) unable to obtain informed consent to participate in this study.

The protocol of this study was approved by the ethics committee of Okayama University (No. KEN1704-034 and KEN1701-037). Written informed consent was obtained from all volunteers participating in this study.

2.2. Test foods

As the test foods, five types of foodstuffs often used in a daily meal in Japan were selected according to the previous study on mixed food mastication [18]. In Japanese meal practice, people tend to prefer several foodstuffs such as those to be masticated in

one. Each subject was instructed to take a mouthful of mixed foodstuffs, which contained cooked rice (3 g), one piece of round-sliced sausage (0.5 cm thick, 1.5 cm in diameter, 1.5 g), one piece of cuboid Tamagoyaki (Japanese hard omelet, 1 g, $1 \times 1 \times 1$ cm), julienne strips of raw cabbage (0.3 g) and one piece of round-sliced raw cucumber (0.5 cm thick, ca. 1.5 cm in diameter, 2.4–3 g). The total amount of approximately 9 g was masticated as one mouthful.

2.3. Masticatory conditions

D-group subjects were instructed to wear their dentures during the experiment. Subjects were instructed to take one mouthful of the test foods listed above at a time with a spoon by themselves and to masticate freely until they wanted to swallow the bolus. They were instructed to expel all the masticated foods from the mouth into a disposable cup when they wanted to swallow the bolus. The number of masticatory strokes before expelling the bolus was counted by an observer and recorded as MS (masticatory strokes). This sample was named the MS-sample and was subjected to particle analysis as described below. Half strokes of MS were calculated and named as half-MS. After expelling the first bolus, subjects were instructed to try the next portion of the test food in the same manner. For this second trial, when the observer counted the half number of MS of the subjects, he halted the subject's mastication and instructed them to expel all the masticated foods from the mouth into a disposable cup. This sample was named the half-MS sample.

2.4. Food particle analysis

Dark-field images of the bolus sample were obtained using a masticatory efficiency evaluation system (SME-003, Shofu, Kyoto, Japan) equipped with a digital camera and a double dark-field illumination system, which allowed evaluation of the size of the particle in wet conditions. The food bolus specimen was collected using a small spoon (1.0 cm^3). Three 1.0 cm^3 specimens were taken from each retrieved food bolus sample for digital imaging. The total volume of the three specimens was slightly less than that of one bolus sample under most of the masticatory conditions. The fourth specimen could not be obtained steadily. For each subject, data analysis was performed four times in total for each bolus sample, i.e., three of which were obtained from each of the three specimens mentioned above and another analysis was performed using accumulated digital particle data of these three specimens. A sample specimen of 1 spoon amount was quoted as a 1-spoon specimen, and sample analysis for accumulated three 1-spoon data is referred to as 1-batch analysis hereafter. The dark field images of the particles were binarized, and the circle-equivalent diameter and area of each particle were automatically calculated in the masticatory efficiency evaluation system. The food particle size index (SI) and homogeneity index (HI) were calculated for each image. Smaller HI values indicate higher homogeneity of the observed particle size, and smaller SI values indicate that food was masticated into smaller particles [21]. In this study, to eliminate the influence of the numbers of particles in the sample, the above index calculation was modified to standardize the parameter value, i.e., the "Number of particles" [21], by multiplying the value by 10/particle counts. To evaluate mastication progress, the percent complete for half-MS was calculated. To evaluate mastication progress, the percent complete for half-MS was calculated. For each HI and SI, the percent complete was calculated as the percent value in half-MS by defining the HI and SI for original test food and MS-sample as 0 and 100%, respectively. For the discrimination of the MS condition from the half-MS condition, the cut-off condition was estimated by combining the values of HI and SI. Shifted

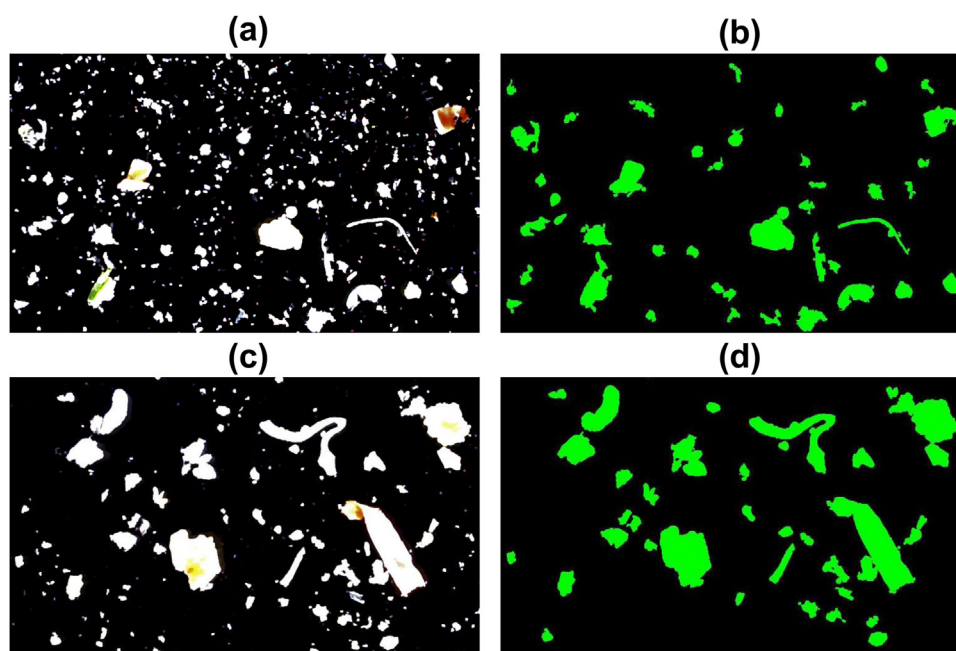


Fig. 1. Typical dark field images and binary images of the particles. (a) Dark field image of a MS-sample, (b) binary image of a MS-sample, (c) dark field image of a half-MS-sample, and (d) binary image of a half-MS-sample.

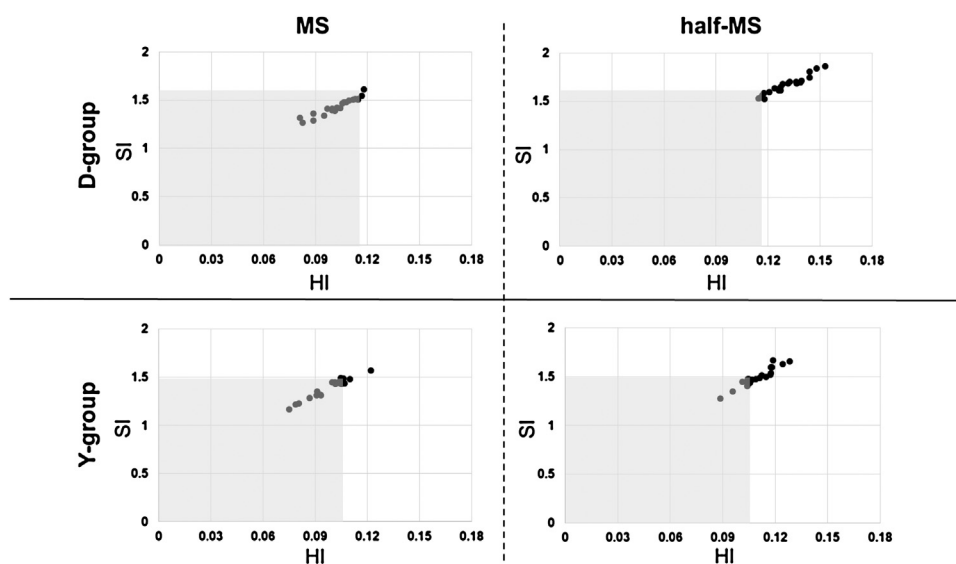


Fig. 2. Scatter plots for HI and SI for the conditions of the MS and half-MS in the D-group and Y-group. The shaded area shows the normal mastication range, which is HI < 0.115 and SI < 1.6 for the D-group and HI < 0.105 and SI < 1.5 for the Y-group. Note that HI and SI for the half-MS in the D-group have higher values than those in the Y-group, suggesting that the D-group particles are more uneven and larger than the Y-group particles.

combinations of HI in steps of 0.005 in the range of 0–0.5 and SI in steps of 0.1 in the range of 0–3 were applied to the data, and the sensitivity and specificity were calculated for each combination of HI and SI. Receiver Operating Characteristic (ROC) curves were used to identify the most appropriate combination of HI and SI for the cut-off.

2.5. Statistical analysis

All variables were tested for distribution normality using the Shapiro-Wilk's test and for homoscedasticity using Levene's test. A

statistical test was conducted to evaluate the difference between each experimental condition using one-way repeated measures analysis of variance (ANOVA) followed by the Tukey–Kramer post hoc multiple comparison test to ascertain significant differences. For the evaluation of the significant difference of the percent complete, ANOVA and multiple post hoc comparisons were made by the Games–Howell test. Student's t-test was used to compare mastication strokes between two groups. Data analyses were performed using SPSS software (IBM SPSS Statistics version 20.0. IBM Japan Ltd., Tokyo, Japan). A significance level of $p < 0.05$ was used in this study.

3. Results

The mean MS for the Y-group was 28.6 ± 12.9 , and the mean MS for the D-group was 39.4 ± 24.6 . MS in the D-group was significantly higher compared with the Y-group. ($p < 0.05$) Breakdown of the D-group based on Eichner's classification was as follows: B3, 3 subjects; B4, 4 subjects; C1, 1 subjects; C2, 10 subjects; and C3, 4 subjects. A typical example of raw dark-field images and binarized images for MS and half-MS are shown in Fig. 1. In the binarized images, only particles with a calculated circle equivalent diameter of 2 mm or more are displayed (Fig. 1b and d). Particles less than 2 mm, which were considered as swallowing threshold, were eliminated from the subsequent analyses as reported in a previous study [21].

Scatter diagrams of HI and SI for MS and half-MS conditions in each group are shown in Fig. 2. Smaller HI values indicate higher homogeneity of observed particle size, and smaller SI values indicate that food was masticated into smaller particles. Thus, dots shown on the lower left indicates well masticated particles in general. In both the Y-group and D-group, dots in MS distributed on the lower left compared with half-MS reveal the legitimate progress of mastication. MS dots in the Y-group and D-group showed similar distribution ranges. However, half-MS dots for the D-group tended to be distributed on the upper right compared with the Y-group, showing lower masticatory performance in the D-group under the half MS condition than the Y-group. In the Y-group, the distribution ranges of half-MS and MS dots tended to overlap with those in the D-group. The shaded area in Fig. 2 shows a normal mastication range calculated for HI and SI. The normal masticatory areas were shown according to the calculated cut-off values of HI and SI to distinguish MS from half-MS.

In this study, 3 specimens from the spoon of 1 bolus were collected. As the numbers of particles were standardized in the modified logic used in this study, the difference in the sampling volume would not affect the results on HI and SI. Table 1 shows the cut-off values for MS and half-MS in the D-group and Y-group, which were calculated using 1-spoon specimens and 1-batch analysis data, respectively. In the Y-group, the cut-off value calculated with 1-spoon specimens was 0.100 for HI and 1.5 for SI. The sensitivity was 0.63, and the specificity was 0.78 with this cut-off value. The cut-off value in the Y-group calculated for 1-batch analysis was 0.105 for HI and 1.5 for SI. The sensitivity was 0.70, and the specificity was 0.70 with this cut-off value. In the D-group, the cut-off value calculated with 1-spoon specimens was 0.115 for HI and 1.6 for SI. The sensitivity was 0.89, and the specificity was 0.88 with this cut-off value. The cut-off value in the D-group calculated for 1-batch analysis was 0.115 for HI and 1.6 for SI. The sensitivity was 0.91, and the specificity was 0.96 with this cut-off value. Although an increase in the amount of analytic sample would logically result in a more accurate result, the cut-off values of HI and SI from 1-spoon specimens showed the same values for 1-batch analysis, thus demonstrating the effectiveness of the modification method applied to the numbers of particles in this study. To avoid redundancy, the following results are shown for 1-batch analysis.

All variables were confirmed to be normality distributed and to be homoscedasticity. Fig. 3 shows the mean and the standard deviation of HI and SI for MS and half-MS conditions in the D-group and Y-group. In the D-group, the mean SI was 1.431 ± 0.087 for MS and 1.656 ± 0.098 for half-MS. In the Y-group, the mean SI was 1.383 ± 0.107 for MS and 1.493 ± 0.099 for half-MS. In the D-group, the mean HI was 0.103 ± 0.011 for MS and 0.129 ± 0.012 for half-MS. In the Y-group, the mean HI was 0.098 ± 0.012 for MS and 0.110 ± 0.009 for half-MS. In both HI and SI, the average value of MS did not show any significant difference between the D-group and Y-group, suggesting that the comminution performance

Table 1. Cut-off values between MS and half-MS in the D-group and Y-group.

	Sample	HI	SI	Sensitivity	Specificity
D-group	1-spoon specimen	0.115	1.6	0.89	0.88
	1-batch analysis	0.115	1.6	0.91	0.96
Y-group	1-spoon specimen	0.100	1.5	0.63	0.78
	1-batch analysis	0.105	1.5	0.70	0.70

immediately before swallowing was not significantly different between the two groups. A significant difference was observed in both HI and SI between the MS and half-MS conditions in the D-group and Y-group ($p < 0.05$). Regarding half-MS, a significant difference in HI and SI was noted between D-group and Y-group ($p < 0.05$), suggesting slower progression of comminution processes in denture wearers than in young dentate subjects.

Fig. 4 shows the percent of complete mastication for each subject in the D-group and Y-group. The percent complete of SI at half-MS was 81.3 ± 2.2 (mean $\pm$ Standard Deviation) for Eichner group B in the D-group, 73.9 ± 1.7 for Eichner group C in the D-group and 87.9 ± 7.8 for the Y-group. The percent complete of HI at half-MS was 50.3 ± 4.0 for Eichner group B in the D-group, 25.6 ± 6.4 for Eichner group C in the D-group and 71.9 ± 14.9 for the Y-group. The percent complete of HI was significantly different among the Eichner group B, Eichner group C and the Y-group ($p < 0.05$). The percent complete of SI for the Y-group was significantly reduced compared with the Eichner group C ($p < 0.05$).

4. Discussion

Comparison of the progression of the comminution process in young dentate subjects and denture-wearing elderly people was conducted in the present study. Previous studies reported an increase in the number of chewing cycles, duration of mastication sequence and EMG activity per sequence in denture wearers, which would be an adaptive process of mastication for denture prosthesis [6,8,22]. The significant increase in the number of mastication strokes in older denture wearers in the present study was consistent with these reports. Chewing efficiency was defined as the number of mastication strokes needed to halve the initial particle size [23].

In the present study, chewing efficiency could not be evaluated. However, the chewing efficiency of two subject groups might be indirectly evaluated by comparing the masticatory cycles necessary to produce boluses comprising a similar particle size distribution. As the properties of bolus particles for the D-group and Y-group, which were expressed as HI and SI, were similar under MS conditions, the chewing efficiency of the D-group could be regarded as lower than the Y-group.

As shown in the percent complete (Fig. 4), difference in half-MS was observed between the Y-group and D-group at half-MS. The difference in the percent complete was particularly large in HI. This finding indicates that particle size was less homogeneous in the D-group compared with the Y-group, especially at half-MS. This finding also indicates that during the first half of the masticatory process in the D-group, chewing strokes were mainly used to achieve nonselective rough comminution. By contrast, given this nonselective comminution observed in the D-group, healthy young dentate subjects appeared to have a more detailed process to recognize the size of food and prioritize larger particles to comminute them into a smaller size. Mishellany et al. [24] reported the cooccurrence of variability of mastication and relative stability of bolus granularity in healthy subjects. They mentioned healthy subjects could adapt mastication to the properties of the food, and chewing the same food produce almost identical

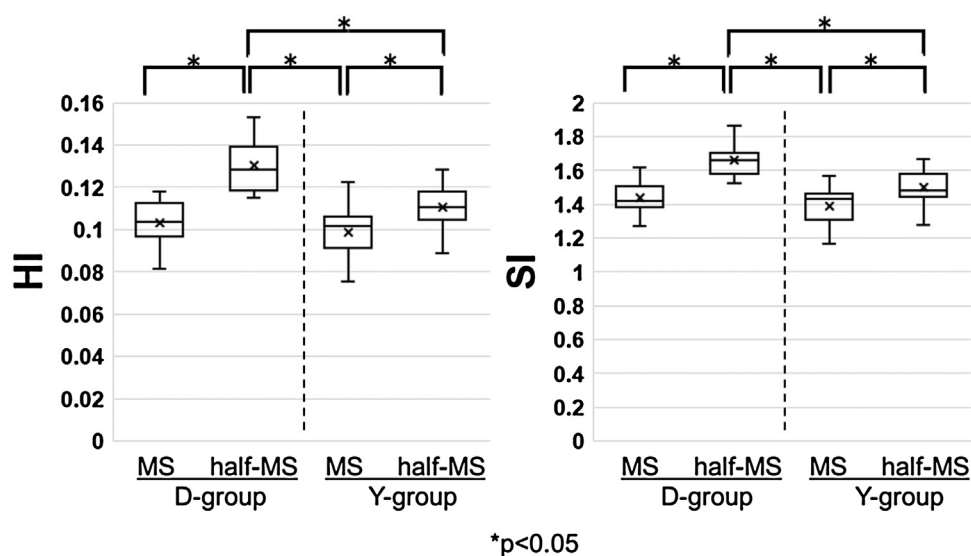


Fig. 3. Mean HI and SI for the MS and half-MS conditions in the D-group and Y-group. Error bars indicate the standard deviation. (*: $p < 0.05$).

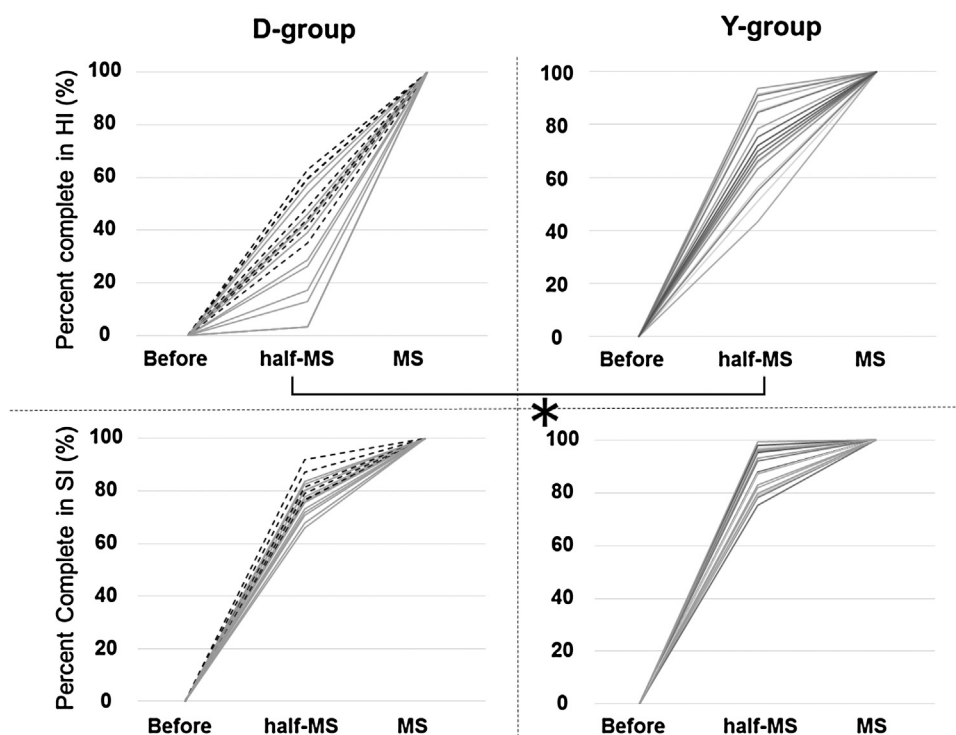


Fig. 4. Percent complete mastication for each condition. In the D-group, the dotted lines represent Eichner group B subjects and the solid lines represent Eichner group C subjects (*: $p < 0.05$).

granularity when confronted with the task of reducing the food to a standard particle size. Therefore, the results of the present study would suggest that the ability to prioritize and select larger food particles was lower in elderly denture wearers for digestion of the adaptation of mastication.

The extent of loss of molar occlusal support appeared to affect the progression of the comminution process. In their study using single test foodstuff, Kapur et al. stated that mastication in subjects with complete dentures is a nonpreferential process, wherein particles of all sizes are ground randomly [7,25]. The nonselectivity observed in this study could be derived from an artificial

compensation for missing teeth and other oral tissue by the removable dentures. Specifically, this finding could be related to the loss of sensory receptors in the periodontal ligament and the blockade of perception of the oral mucosa by the denture base, but further research will be necessary to further elucidate this notion.

In this study, mastication was evaluated by analyzing food particle size using a method modified from that reported by Sugimoto et al. [21]. It was reported that image analysis could provide similar cumulative volume or weight curves that would be comparable to a physical sieving method [26,27]. As this method does not require drying of the food particle, most of the foodstuffs

taken in a daily meal could be applied for evaluation. Regarding the evaluation method for the particle analysis on mastication, $\times 50$ is one of the most frequently used methods in this field [28]. Here, $\times 50$ is an excellent method to characterize the particle size distribution with one representative value [29]. On the other hand, it is possible to evaluate two indices, particle homogeneity and size, separately using this method. The results of this study revealed a clear difference in particle homogeneity rather than particle size. This feature would be a distinguishing property of the homogeneity index for characterizing masticatory results, especially when we need to design food cuisines for patients with masticatory disorders. The retrieval rate of masticated test food is often an important factor that affects the results of the analysis of mastication efficiency. For example, Manly's method using peanuts [11] needs to retrieve a total sample from the oral cavity after mastication. Peyron et al. reported using natural foods such that the retrieval rate after the complete mastication sequence was approximately 40% of the initial weight [30]. Several studies reported higher retrieve rates using silicone dental impression material as artificial test food [31]. However, Bonnet et al. stated that the use of non-edible test material would be debatable, especially in the studies that aim to investigate swallowing threshold [29]. They mentioned synthetic materials, such as dental impression materials, were not supposed to be swallowed but induce nonnutritive mastication that generally depends on voluntary command and is more detached from neuro controls compared with mastication of natural food. In these conditions, the swallowing threshold is not realistic, as the subjects cannot adapt the kinematic parameters with reference to a previous experience of swallowing such materials.

In the physical sieving method, curve-fit using the size distribution of industrial breakage products has often been adopted to compensate for missing particle size data [29,32]. In principle, a higher retrieval rate would result in a more accurate estimation of the masticatory function. However, in the case of evaluating chewing of significantly elderly people, it is often difficult to accurately collect the whole amount of test food bolus. Therefore, it would be more practical and helpful to establish a method that can accurately evaluate masticatory performance with the limited retrieval amount of test food. In the present study, to improve the original method to evaluate masticatory performance [21], standardization of the coefficient was adopted in this study using the number of particles, so that the change in the total number of particles in the sample would have less of an effect on the analysis results.

In this study, we examined the amount of a bolus sample using both a 1-spoon specimen and 1-batch analysis with three 1-spoon specimens. Although we only presented the results using 1-batch analysis, the results obtained from the 1-spoon specimens were not different. Therefore, the standardization of the particle number adopted in this study was effective. In addition, these results suggest that 1-spoon sampling is acceptable in future studies using this method. However, only limited data using the present evaluation method are available to date; therefore, future studies investigating the relationship with X50, which has been already established in numerous experimental studies, are expected.

In this study, the HI and SI cut-off values for discriminating between the MS and half-MS conditions were calculated. In previous reports on food bolus particle analysis using healthy young adults [18,21], the area on the analytical scatter plot of HI < 0.10 and SI < 1.62 for each experimental condition was defined as the normal range. When we recalculated the data in their reports [18,21] using the modified analysis method, the cut-off value was 0.105 for HI and 1.5 for SI. These values for the young healthy dentate group were consistent with the cut-off value (HI: 0.105 SI: 1.5) calculated in this study. The cut-off value of HI and SI for denture-wearing elderly people was calculated for the first time in

this study. The cut-off values of 0.115 for HI and 1.6 for SI resulted in the discrimination of MS from half-MS with a sensitivity of 0.91 and a specificity of 0.96. The slight difference in the cut-off value between the Y-group and D-group is consistent with the difference in the bolus particle size between denture wearers and natural dentate subjects in previous studies [5,33].

A limitation of this study was the establishment of group age. A fully dentate group was collected from young healthy volunteers for comparison with denture-wearing elderly people. Two possible reasons might have contributed to the significant difference in the progress of mastication at half-MS between the Y-group and D-group. One explanation is the presence or absence of dentures, and the other is the difference in the physiological properties of subjects related to their ages. In the present study, the young healthy dentate group was used as the control group because it was rare to recruit age-matched elderly people with a full dentate. However, in a previous study, Fontijn-Tekamp et al. [34] reported that an age difference of greater than approximately three decades minimally affected the bite force and chewing efficiency. Peyron et al. also reported in their review that aging itself had little impact on the ability of subjects to grind brittle foods into small particles [8]. Although it might be possible to infer that the results for the young dentate group in this study could be applicable to full dentate elderly people, further investigations with age-matched controls are needed.

5. Conclusions

From the results of the present study, the progression of the comminution process in denture-wearing elderly people was different from that in young dentate subjects. These findings are especially useful for examining or planning food forms for patients with masticatory disorders. Future studies to investigate the relationship between the analytical method adopted in this study and X50, which has been established in numerous experimental studies, are expected.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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