Effects of food particle loss on the evaluation of masticatory ability using image analysis

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Abstract

Purpose: To examine how particle loss affects the evaluation of masticatory ability using the image analysis method.

Methods: The subjects were divided into two groups: Y-group (healthy young adults: 10 male, 10 female; mean age 27.6 ± 1.9 years), and D-group (denture wearing older adults: 13 male, 9 female; mean age, 75.1 ± 5.3 years). Raw carrots, peanuts, and a combined test food from 5 daily food materials (mixed foods) were selected as test foods. Images of the boluses were captured and processed after the subjects freely masticated the test foods until the point of swallowing or completed half strokes of total chewing cycles. The median particle size (X50) was calculated from the data for each particle. We compared X50 calculated from all particles obtained from the masticatory bolus (as X50N) with the X50 of only selectively larger particles (as X50R).

Results: Significant correlations were observed between X50N and X50R (p < 0.01) determined in almost all masticatory conditions. In particular, for particle sizes of 2 mm or more, the correlation coefficient between X50N and X50R was notably strong (r > 0.75).

Conclusion: The method of analyzing only larger particles makes it possible to evaluate masticatory ability without losing the characteristics of the original particle size distribution of the entire bolus. This finding can be applied for the evaluation of masticatory ability, especially among older adults who have difficulty retrieving the total amount of test food due to decreased activities of daily living.

Keywords: Particle size, Mastication, Masticatory ability, Denture, Oral function

1. Introduction

Mastication is a part of digestive motility and an important function that is involved in quality activities of daily living (ADL), especially in older adults [1]. Accurate evaluation of the masticatory ability of each individual would assist in the maintenance and improvement of masticatory ability. Various methods have been used to evaluate the masticatory ability of an individual, which can be roughly classified into two types: The first one is a direct evaluation method that expresses the state of the masticated sample as an objective numerical value. The second is an indirect evaluation method that measures masticatory ability based on parameters of oral functions such as muscle activity, occlusal force, or jaw movement. As mastication is a complex process, in the former method, the masticatory function has been evaluated from various aspects, including pulverization, biting, or mixing. In recent studies, evaluation methods that focus on mixing ability using materials such as wax cubes and color-changeable chewing gum have been considered [2,3]. Dental silicone impression materials and gummy jelly have often been used to evaluate pulverization orbiting [4,5]. Using these artificial materials for the evaluation of mastication is simple and hygienic [4]. However, the existing drawback of these methods is that it would be rather difficult to comprehensively evaluate the whole masticatory function because these methods focus on rather limited aspects of natural mastication. It has also been reported that chewing behavior during artificial material mastication could differ from that of natural foods [6]. Therefore, it would be more practical to evaluate the masticatory ability of natural foods. Several studies have evaluated the masticatory ability of natural foods as test foods. The most classical method is the sieving method, which measures and evaluates the size of the bolus particles [7].

The size distribution of the food bolus particles has been reported as one of the triggering factors for deglutition; therefore, measuring food bolus particle size is considered the “gold standard” for objective evaluation of mastication [8]. Several researchers have incorporated this evaluation method into their studies. Another technique for particle size measurement is the image analysis method. Because the size of each particle can be automatically recognized on a computer, the analysis procedure is simpler than that of the conventional sieving method. In particular, the image analysis method proposed by Sugimoto et al. enables analysis under wet conditions and makes it possible to omit the time-consuming drying process [9]. Using this method, Sugimoto et al. revealed the difference in...
the characteristic comminution progress between older and young people, using a combination of various natural test foods similar to an actual meal [10]. The retrieval rate of masticated particles from the mouth has been an inherent issue in investigating comminuted food particles. Using natural foods, Peyron et al. reported that after a complete mastication sequence, the retrieval rate was approximately 40% of the initial weight [11]. This limited overall retrieval rate may be attributed to 1) handling the particles and 2) the difficulty of the retrieval process of the particles from the subject’s mouth. The former represents the effects of the complicated sieving steps of the conventional sieving method and the drying process of natural foods [12]. The latter shows that minutely pulverized particles are sometimes rather difficult to perceive by subjects, including the influence of intermediate swallowing during chewing or possible stage II swallowing [11]. When evaluating the masticatory ability of older adults with reduced ADL, it would be more difficult to retrieve the entire bolus because of the possible decrease in oral perception or compliance with the experimental instructions. Well-comminuted small food particles have been reported to be easily enrolled in stage II transport [13]. Therefore, an evaluation technique involving analysis of only larger particles, which would be difficult to be lost in the mouth even in older people, would be of social demand in a super-aged society.

This study aimed to compare the evaluation method of image analysis processing between all particles obtained from the masticatory bolus and the selectively larger particles and examine how particle loss affected the evaluation of masticatory ability. The research hypothesis was that “there was no significant difference in the evaluation method of image analysis processing between all particles obtained from the masticatory bolus and only the larger particles.”

2. Material and Methods

2.1. Subjects

The subjects were divided into two groups according to age. The healthy young dentate group (Y-group) consisted of 20 volunteers (10 of each gender; mean age, 27.6 ± 1.9 years) of staff and students who belonged to Okayama University Hospital. Another group consisted of 22 denture-wearing older subjects (13 males and 9 females, mean age 75.1 ± 5.3 years) of staff and students (10 of each gender; mean age, 27.6 ± 1.9 years) of staff and students, Japan) equipped with a digital camera was used for image capturing and analysis of the bolus particles. This device automatically generated binarized images from raw digital images and calculated each particle size. First, the food bolus obtained from each subject was rinsed with two types of surfactants. The obtained sample had to be divided into three portions because the image capturing pool was not sufficiently large to disperse one whole bolus. Three specimens measuring 1.0 cm3 for digital imaging were taken using a small spoon of the same volume from each retrieved food bolus sample. The obtained raw digital image was binarized, and the virtual circle-equivalent diameter and area of each particle were automatically calculated in the device. Data analysis was performed using the particle size data for all the particles included in the three specimens for each subject.

Two independent methods were used for particle analysis. The

Written informed consent was obtained from all subjects.

2.2. Test foods

Natural foods, such as raw carrots and peanuts, have been widely used for several years to measure masticatory ability and were selected as single test food ingredients for this study.

Five raw carrot cuboids (1×1×2 cm each) and five peanut pieces (weighing approximately 4 g) were used. A combination of five different test foods (mixed food) often used in Japanese daily meals was also selected as a test food, based on a previous study on mastication of mixed food [10,15]. The mixed food consisted of cooked rice (3 g), one piece of round-sliced sausage (0.5 cm thick, 1.5 cm diameter, 1.5 g), one piece of cuboid Tamagoyaki (Japanese hard omelet, 1 g, 1×1×1 cm), julienne strips of raw cabbage (0.3 g), and one piece of round-sliced raw cucumber (0.5 cm thick, 1.5 cm diameter, 2.4-3 g). A total of approximately 9 g was masticated as one mouthful [15]. In this study, the Y group was subjected to peanut, carrot, and mixed food as the test food, and the D-group was subjected to mixed food.

2.3. Masticatory conditions

During the examination, the subjects in the D group used their dentures during mastication. All subjects were instructed to take a single dose of the test food into their mouth at once using a spoon and freely masticate until they wanted to swallow the bolus. They were instructed to expel all the masticated food in the mouth into a disposable cup when they felt like swallowing the bolus. The experimenter visually confirmed that no particles remained in the oral cavity after the subject expelled the bolus. Before expelling the bolus, the number of chewing strokes was counted by an observer and recorded as masticatory strokes (MS). This sample was designated as the MS sample and subjected to particle analysis, as described below. Half strokes of mastication were calculated as half-MS, which was set assuming the condition of masticatory disorders.

After the first examination, the subject was instructed to try the next portion of the test food in the same manner. In the second trial, when the examiner counted half of the MS, the subject was instructed to stop mastication and expel all the bolus in the mouth into a disposable cup. This sample was termed the half-MS sample.

Two independent methods were used for particle analysis. The

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first method involved utilizing the food particle size index (SI) and homogeneity index (HI). These indices were obtained from the linear regression of the particle size distribution proposed by Sugimoto et al. [9]. Smaller HI values indicate higher homogeneity of the observed particle size, and smaller SI values indicate that food was masticated into smaller particles. As a principle of analysis, this method uses the data of particles with diameters larger than 2 mm.

Another method was to calculate the median particle size ($X_{50}$), estimated from the particle diameter corresponding to the center of the cumulative distribution of the volume of all particles included in a bolus. The $X_{50}$ value calculated from all particles obtained from one bolus was expressed as $X_{50N}$, and the $X_{50}$ value calculated from the selected particle size range was expressed as $X_{50R}$ (lower limit of the particle size). For example, $X_{50R}$ (2.0) was defined as $X_{50}$ calculated from 2.0 mm or larger particles in a bolus. In the present study, $X_{50R}$ (2.0), $X_{50R}$ (2.5), $X_{50R}$ (3.0), and $X_{50R}$ (4.0) were calculated.

**2.5. Statistics**

Data distribution normality of HI/SI and $X_{50}$ calculated for each food, masticatory period (MS, half-MS), and the subject group was examined for normality using the Shapiro–Wilk test. Spearman’s rank correlation test was performed to investigate whether there was a statistically significant correlation between HI/SI and $X_{50N}$ and between $X_{50N}$ and $X_{50R}$ for each masticatory condition. Data analyses were performed using the Statistical Package for the Social Sciences software (IBM SPSS Statistics version 20.0. IBM Japan Ltd., Tokyo, Japan). A significance level of $p < 0.05$ was considered in this study.

**3. Results**

No adverse events were observed in any of the subjects during the mastication test. The D-group was classified according to Eichner’s classification. Seven subjects belonged to Eichner’s group B, and 15 subjects belonged to Eichner’s group C. A typical example of the obtained bolus image, binarized image, and particle selection process is shown in Figure 1. The raw image in Figure 1(a) illustrates the entire area of the sample dispersion pool for one spoon sample.

Table 1 lists the average number of MS, HI/SI, and $X_{50N}$ at each mastication condition. Among the test foods, peanuts showed the smallest values of HI, SI, and $X_{50}$, and mixed food in the older adults showed large values. Table 2 shows the correlation between $X_{50N}$, HI, SI, and $X_{50N}$ and HI/SI showed a significant correlation ($p < 0.01$) with $X_{50N}$ in all masticatory conditions. The lowest correlation coefficient ($r = 0.714$) between SI and $X_{50N}$ was observed for the Y-group carrot half-MS sample.

Table 3 shows the correlation between $X_{50N}$ and $X_{50R}$. Two typical examples of scattered plots are shown in Figure 2. The lowest correlation coefficient ($r = 0.441$) between $X_{50N}$ and $X_{50R}$ (4.0) was observed for the peanut MS sample, as shown in Figure 2(b). The mixed-food half-MS sample of the Y-group exhibited the highest correlation coefficient ($r = 0.998$) between $X_{50N}$ and $X_{50R}$ (2.0), as illustrated in Figure 2(a). As shown in Table 3, significant correlations were observed under all masticatory conditions between $X_{50N}$ and $X_{50R}$ except for $X_{50R}$ (4.0) in peanut MS. As shown in Table 3, the larger-sized samples obtained by elimination of small particles resulted in a lower correlation coefficient between the original $X_{50N}$.
Furthermore, the peanut MS bolus, which exhibited the lowest HI, SI, and X50N (Table 1), showed the lowest correlation coefficients between X50N and X50R.

4. Discussion

In this study, carrots, peanuts, and mixed foods were selected as the test foods. As carrot and peanuts have been widely used in studies involving the determination of masticatory ability, an enormous amount of knowledge on particle size is available. It is well known that peanuts are friable and tend to produce very fine particles after mastication. Regarding the test food carrots, Prinz et al. reported a standard size of 1.4 mm to 2.0 mm for particles to be swallowed safely [16]. Accordingly, we adopted a particle size of 2.0 mm as one of the different particle sizes used in this study. The mixed food was used to represent an actual diet, and we reported on the particle size distribution using this mixed food in our previous studies [10,15]. Younger and older adults without any subjective or objective difficulties in mastication were selected for this study. It has been reported that younger edentulous individuals have stable jaw movement paths and masticatory rhythms with the high masticatory ability [17]. However, another previous study suggested that the particle size distribution of the bolus immediately before swallowing was essentially dependent on the type of food but not on healthy adults without

| Table 2. Correlation between X50N and HI or SI |
|-----------------------------------------------|
|                               | X50N and HI | X50N and SI |
|                               | r          | P-value     | r          | P-value     |
| Y-group Carrot MS              | 0.956      | <.01*       | 0.953      | <.01*       |
|                               | 0.827      | <.01*       | 0.714      | <.01*       |
| Peanuts MS half-MS             | 0.865      | <.01*       | 0.875      | <.01*       |
|                               | 0.913      | <.01*       | 0.934      | <.01*       |
| Mix food MS half-MS            | 0.946      | <.01*       | 0.86       | <.01*       |
|                               | 0.919      | <.01*       | 0.914      | <.01*       |
| D-group Mix food half-MS       | 0.901      | <.01*       | 0.866      | <.01*       |
|                               | 0.796      | <.01*       | 0.72       | <.01*       |

* significant correlation.

| Table 3. Mean and standard deviation of restricted X50 and correlation to the X50N |
|-----------------------------------------------|
| Masticatory condition (Restricted particle size) | Restricted X50 Mean ± SD (mm) | Correlation coefficient | P-value |
| Y-group Carrot MS (2.0) | 4.997 ± 1.531 | 0.982 | <.01* |
| (2.5) | 5.196 ± 1.332 | 0.974 | <.01* |
| (3.0) | 5.467 ± 1.449 | 0.959 | <.01* |
| (4.0) | 5.992 ± 1.379 | 0.963 | <.01* |
| Half (2.0) | 7.118 ± 1.653 | 0.977 | <.01* |
| (2.5) | 7.207 ± 1.609 | 0.952 | <.01* |
| (3.0) | 7.345 ± 1.493 | 0.922 | <.01* |
| (4.0) | 7.562 ± 1.421 | 0.901 | <.01* |
| Peanuts MS half-MS (2.0) | 3.172 ± 0.649 | 0.759 | <.01* |
| (2.5) | 3.552 ± 0.575 | 0.696 | <.01* |
| (3.0) | 3.967 ± 0.552 | 0.705 | <.01* |
| (4.0) | 4.724 ± 0.636 | 0.441 | 0.053 |
| Half (2.0) | 5.747 ± 2.755 | 0.986 | <.01* |
| (2.5) | 6.192 ± 2.735 | 0.980 | <.01* |
| (3.0) | 6.483 ± 2.591 | 0.979 | <.01* |
| (4.0) | 7.093 ± 2.391 | 0.919 | <.01* |
| Mix food MS (2.0) | 4.929 ± 0.678 | 0.923 | <.01* |
| (2.5) | 5.093 ± 0.653 | 0.923 | <.01* |
| (3.0) | 5.327 ± 0.665 | 0.861 | <.01* |
| (4.0) | 5.892 ± 0.778 | 0.777 | <.01* |
| Half (2.0) | 5.840 ± 0.666 | 0.972 | <.01* |
| (2.5) | 5.958 ± 0.583 | 0.961 | <.01* |
| (3.0) | 6.099 ± 0.611 | 0.944 | <.01* |
| (4.0) | 6.452 ± 0.538 | 0.900 | <.01* |
| D-group Mix food MS (2.0) | 5.345 ± 0.803 | 0.983 | <.01* |
| (2.5) | 5.497 ± 0.805 | 0.958 | <.01* |
| (3.0) | 5.707 ± 0.865 | 0.966 | <.01* |
| (4.0) | 6.220 ± 0.859 | 0.906 | <.01* |
| Half (2.0) | 8.676 ± 2.025 | 0.988 | <.01* |
| (2.5) | 8.738 ± 1.982 | 0.981 | <.01* |
| (3.0) | 8.930 ± 2.036 | 0.963 | <.01* |
| (4.0) | 9.229 ± 2.035 | 0.962 | <.01* |

* significant correlation.
The median particle size (X₅₀ in this study) is generally calculated from the particle weight integration distribution in the classical sieving method. In contrast, the image analysis method is calculated from the volume integration distribution [21]. With regard to the evaluation method of X₅₀, the volume of each particle was calculated from the equivalent circle diameter of the particles. Considering it as a sphere from the equivalent circle diameter of the particles, the volume of each particle was calculated.
the particle image in this study. This means that the calculated volume is an estimate, indicating the difference between this value and the actual particle volume. However, a previous study comparing the image analysis method with the traditional sieving method suggested compatibility between the two methods [22]. Furthermore, the X50 obtained in this study did not show a considerable difference from that obtained using the sieving method, which was reported in a previous systematic review [6]. Therefore, the X50 value in this study can be considered reliable to some extent.

In this study, a dedicated device was used to obtain standardized images for image evaluation. An easily available imaging device such as a digital camera or a smartphone with camera functions should be used. The bolus processing process, such as rinsing and stirring, is as simple as possible for widespread application in daily clinical practice. Further modifications are required to establish the evaluation method.

In this study, peanuts were selected as food that tended to have small particles after mastication and was easily affected when only the larger particles were considered in the analysis process. As a result, it can be concluded that even analyzing particles of size 2 mm or more is useful for understanding the masticatory ability of each individual. Since this conclusion is based on the peanut bolus consisting of the smallest particles, this result may not be consistently applied to all foods. The particle size distribution of other friable foods may be smaller than that of peanuts. In the future, further studies addressing this issue are needed; however, it is unlikely that it will have a significant impact on the evaluation criteria because friable nuts would not be a regular diet in daily life. It has been reported that older people are less accepting of particularly hard foods and tend not to take in them intentionally [23]. This was due to several factors in the oral cavity (i.e., number of remaining teeth, periodontal disease, prostodontic state) and general conditions such as frailty [23,24]. A previous study showed that older people with a complaint of xerostomia have difficulty chewing and tend to avoid eating crunchy, hard, dry, or sticky foods [25]. Considering the test foods from the viewpoint of rheology, a diet with too much hardness or viscosity may not be suitable as a test food in terms of evaluating the daily eating habits of the elderly. In addition, it is necessary to separate the particles so that they do not overlap while taking an image when using the image analysis method. There is a methodological limitation on using test foods that are hard to separate particles due to their strong cohesiveness and stickiness. Therefore, when evaluating the masticatory ability of the elderly using this method, the selection of the test food is of critical importance.

In this study, the bolus retrieval rate based on the weight of the original test food was not specifically measured. As mentioned above, it is ideal for analyzing all food particles during mastication. Peyron et al. reported that the bolus weight immediately before swallowing when using several whole foods was only 40% of the initial weight [11]. Furthermore, they reported that the decline in bolus retrieval rates was due to intermediate swallowing. Intermediate swallowing is the swallowing movement resulting from stage II transport. Mishellany et al. reported that the food bolus mass retrieved after the mastication test was 87% for peanuts and 68% for carrot, based on an in vitro study using mastication simulators [26]. The release of water content in food caused by artificial chewing resulted in the loss of food mass. Liu et al. reported that the retrieval rate after chewing and before sieving food bolus was more than 90% when using artificial foods that were not easily affected by saliva and processes of rinsing and drying [27]. Considering that artificial materials do not induce swallowing, a small percentage of the weight that could not be collected would remain in the oral cavity. Therefore, the main causes of weight loss observed when using natural test foods are difficulty retaining water inside food and swallowing during stage II transport. It isn’t easy to control the amount of water present in food because of the characteristics of natural foods, regardless of whether it is dry or wet in weight measurement. Considering the difference in retrieval rate of several tens of percent, weight comparison of natural foods before and after mastication is likely to be poorly reproducible. However, wet conditions are more advantageous in image analysis than dry conditions because they reflect the original size of the particles. Additionally, in studies where the subjects were instructed to chew until before swallowing, and intermediate swallowing was not permitted, it was difficult to control the process of mastication in individuals completely. Likewise, Tanaka et al. reported no significant difference in particle size between stage II transport and the oral cavity immediately before swallowing in healthy subjects [13]. From the above, it can be suggested that this method makes it possible to sufficiently analyze masticatory abilities without impairing the characteristics of the original particle size distribution by using even the discharged bolus, including larger particles in healthy subjects with normal oral function.

The subjects were healthy adults without decreased ADL and instructed to spit out the entire bolus as much as possible without any specific instructions in this study. We did not examine how the subjects spit out the bolus more closely. On the other hand, the way to spit out the bolus should be considered in the case of elderly people with frailty. It is difficult to set experimental conditions for elderly people with frailty in a study conducted on healthy subjects. Further studies are necessary to focus on subjects with frailty to evaluate their masticatory ability.

5. Conclusion

The results of this study suggest that the analysis of bolus particles of 2 mm or more makes it possible to evaluate masticatory ability without changing the characteristics of the particle size distribution of the entire bolus. This finding is expected to be applied when evaluating masticatory ability, particularly in older adults with decreased ADL. It is difficult to collect the entire amount of the test food. It can be noted that there is an increasing demand for a reliable method to evaluate masticatory ability by analyzing larger particles that can be collected without exception, and further applications of the image analysis method are expected in the future.

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Conflicts of interest

The authors declare no conflicts of interest.

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