Study of occlusal acoustic parameters in assessing masticatory performance

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Abstract

Background: Previous masticatory studies have focused on a variety of measurements of foods and boluses or kinematic parameters and sound during mastication. To date, the masticatory sound research of has been limited due to the difficulties of sound collection and accurate analysis. Therefore, significant progress in masticatory sound has not been made. Meanwhile, the correlation between acoustic parameters and mastication performance remains unclear. For the purpose of exploring the acoustic parameters in measuring mastication performance, the bone-conduction techniques and sound analysis were used, and a statistical analysis of acoustic and occlusal parameters were conducted.

Methods: The gnathosonic and chewing sounds of fifty-six volunteers with healthy dentate were recorded by a bone-conduction microphone and further analyzed by Praat 5.4.04 when intercussally occluding natural foods (peanuts) were consumed. The granulometry of the expectorated boluses from the peanuts was characterized by the median particle size of the whole chewing sequence (D50a) and the median particle size during the fixed chewing strokes (D50b). The chewing time of the whole chewing sequence (CTa), the chewing time of the fixed chewing strokes (CTb), the chewing cycles (CC), and the chewing frequency (CF) were recorded and analyzed by the acoustic software. The acoustic parameters, including gnathosonic pitch, gnathosonic intensity, mastication sound pitch of the whole chewing sequence (MPa), mastication sound pitch of the fixed chewing strokes (MPb), mastication sound intensity of the whole chewing sequence (MIa) and mastication sound intensity of the fixed chewing strokes (MIb), were analyzed. Independent sample t-test, Spearman and Pearson correlation analyses were used where applicable.

Results: Significant difference in parameters CC, MIa, CF and D50a were found by sex (t-test, p < 0.01). The masticatory degree of the test foods was higher in women (CC, 24.25 ± 5.23; CF, 1.70 ± 0.21 s⁻¹; D50a, 1655.07 ± 346.21 μm) than in men (CC, 18.14 ± 6.38; CF, 1.48 ± 0.18 s⁻¹; D50a, 2159.21 ± 441.26 μm). In the whole chewing sequence study, a highly negative correlation was found between MIa and D50a, and a highly positive correlation was found between MIa and CF (r = −0.94, r = 0.82, respectively, p < 0.01). No significant correlation was found between the remaining acoustic parameters and mastication parameters. In the fixed chewing strokes study, a highly negative correlation was found between MIb and D50b (r = −0.85, p < 0.01). There was no significant correlation between the rest of the acoustic parameters and the mastication parameters.

Conclusions: Mastication sound intensity may be a valuable indicator for assessing mastication. Acoustic analysis can provide a more convenient and quick method of assessing mastication performance.

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Introduction
Restoring the ability to masticate food is one of the primary goals of dental treatment. Masticatory performance is defined as the ability to comminute test food [1]. In contrast to the early common method for assessing masticatory performance, which is a comminution method using a sieve [2], recent alternatives to the sieve method were introduced for assessing the particle size distribution. The main methods of assessing bolus particle include the digital scanning, spectrophotometer measurement of released dye and glucose released from fragmented test food particles [3–5]. In addition, the degree of mixing has been suggested as another way to assess mastication, which uses color-changeable chewing gum and two-color wax or gum as the test food [6–8]. Compared with mixing testing, the sieve method is probably better suited for research in recent studies [9, 10]. Recently, the method of bolus granulometry analysis, which is expressed as the D50 value, characterizes the test-food theoretical sieve size and the measurement of kinematic parameters before swallowing, which produces the bolus, has appeared to provide a good criterion for objectives with normal mastication [1, 11]. Therefore, bolus granulometry analysis combined with kinematic parameters may be an useful approach for further assessing masticatory performance.

Previous acoustic studies of occlusal sounds concentrated on gnathosonic and chewing sounds. Gnathosonic features the use of sounds generated as the teeth meet as an analogue of the quality of the occlusion [12]. The study of gnathosonic focused on occlusal interference and stability [13–16]. Other studies of chewing sound focused on the area of food texture and the relationship between mastication and swallowing [17–19]. However, the acoustic parameters were suggested to be merely reference indices during the observation of mastication behaviour, and there has been no further exploration of the relationship with masticatory performance in the previous studies [13–19]. Moreover, as a limitation of adapterization and analysis software in early research, it lacked research using complete sound capture and further analysis of acoustic parameters [20].

Based on the doubts about acoustic processing methods, the bone-conduction tech, which establishes an independent path of adapterization and provides a wider spectrum to annotate sound data, may be a good solution. In addition, the solid sound produced by occlusion could be collected purely through a bone-conducted microphone and could avoid rustling sounds in the air at the same time [21, 22]. Apart from improvements of the hardware, the new acoustic software provides a better way to calculate the sound frequencies, and the parameter of sound intensity were added during the experimental data processing which describes the loudness of the sound and directly reflects the energy of the soundwave for the sake of single data analysis in a previous study [23].

For the purpose of improving the study of occlusal sound, the bone-conduction tech was introduced to capture a more complete sound signal. Meanwhile, based on a previous study of occlusal sound, in which the acoustic parameter expressed a close connection with mastication, this study focused on the relationship between the masticatory performance and the occlusal sound signal. The possibility of evaluation of mastication by acoustic parameters was further explored. Additionally, we found that the acoustic signal could be captured and analyzed more completely and easily through measurements of the test-food bolus.

Materials and methods
Fifty-six volunteers (28 men and 28 women) aged between 20 and 30 were recruited. All participants had complete natural dentition and had no functional mastication problems or dental restoration history. All participants had a normal overjet, overbite and Angle I molar relationship and could chew without unilateral mastication.

Every subject masticated 4 raw peanuts (weight 2.24±0.16 g) from the start of chewing to the point before swallowing as naturally as possible, and the chewed boluses before swallowing were collected. Then, the subject chewed the same number of peanuts 21 times, which was the average time calculated from the former study, and the chewing sounds and bolus were collected as above.

A bone-conduction microphone from BONE VIBRATION HEADGEAR (Model: HG17BN-TX developed by TEMCo INDUSTRIAL LLC) [24, 25] linked to the recording device of SONY ZOOM H4n (Model: Dedicated Zoom AD-14 AC Adapter developed by Sony Group Corporation) was attached to the preauricular skin, which was used for recording the chewing sounds and gnathosonic (Additional file 1: Fig S. 3) [13–19]. Chewing sounds were captured by putting peanuts into the mouth to start chewing. Each gnathosonic was first recorded 10 times with mock chewing without any test...
food. All sound data were recorded in monochannel with an 8000 Hz sampling frequency and 16 bit sampling precision by the bone-conduction device.

After the collection of the acoustic parameters, the parameters were processed in Praat 5.4.04 (developed by Paul Boersma and David Weenink Phonetic Sciences, Division of Humanities, University of Amsterdam, Netherlands) [24, 25], to calculate the gnathosonic pitch (GP), gnathosonic intensity (GI), mastication sound pitch of the whole chewing sequence (MPa), mastication sound pitch of the fixed chewing strokes (MPb), mastication sound intensity of the whole chewing sequence (MIa) and the mastication sound intensity of the fixed chewing strokes (MIb).

Praat 5.4.04 was also used for the evaluation of kinematic parameters. The number of chewing cycles (CC), the chewing time of the whole chewing sequence (CTa) and the chewing time of fixed chewing strokes (CTb) were monitored and annotated accurately on the sound oscillogram by Praat. To calculate the chewing frequency (CF), CTa was divided by CC in the statistics of each subject.

After rinsing with saliva through a 100-μm sieve in water, the chewed bolus was collected. After drying at 80 °C for 30 min, the bolus of each sample was dispersed on a transparent A4 acrylic sheet and then scanned to construct a 600 dpi image. With the analytical result from the images by Powdershape® (Model: Ringstrasse 29 CH-7324 Vilters developed by Innovative Sintering Technologies Ltd., Switzerland), the food bolus granulometry particle size and distribution were further evaluated in the manner of the median particle size value of the whole chewing sequence (D50a) and the median particle size value of fixed chewing strokes (D50b) which expressed the theoretical sieve size that would let through 50% of the particle weights. Thus, D50a and D50b decreased as the theoretical sieve size that would let through 50% of the particle weights. Thus, D50a and D50b decreased as the food boluses contained more small particles.

As seen in Table 2, Independent t-test indicated that no statistically significant differences in CTa, MPa, GP, or GI were found when comparing the parameters between different genders. There were statistically significant difference in CC, MIa, CF and D50a by gender.

### Table 1: Age and mean values for acoustic parameters, kinematic parameters and D50a (n=56) for study of the entire chewing sequence

| Parameters         | Mean ± SD |
|--------------------|-----------|
| Age, years         | 26.5 ± 1.7 |
| D50a (μm)          | 1907.14 ± 468.10 |
| Kinematic parameters |            |
| CC                 | 21.20 ± 6.55 |
| CTa (s)            | 13.29 ± 3.75 |
| CF(s⁻¹)            | 1.59 ± 0.22 |
| Acoustic parameters |            |
| MIa (dB)           | 61.00 ± 4.66 |
| MPa (Hz)           | 2234.30 ± 671.67 |
| GI(dB)             | 54.76 ± 5.21 |
| GP(Hz)             | 2906.50 ± 754.71 |
Table 2  Mean values (± SD) of D50a, GP, GI, MPa, MIa, CC, CTa and CF of the whole chewing sequence with the quantitative food by gender

| Parameters | Mean ± SD | Independent Samples t test | Comparisons |
|------------|-----------|-----------------------------|-------------|
|            | Male (n = 28) | Female (n = 28) |                          |
| D50a (μm)  | 2159.21 ± 441.26 | 1655.07 ± 346.21 | *< 0.01 |
| CC         | 18.14 ± 6.38 | 24.25 ± 5.23 | *< 0.01 |
| CTa (s)    | 12.33 ± 4.45 | 14.26 ± 2.63 | NS* |
| CF (s⁻¹)   | 1.48 ± 0.18 | 1.70 ± 0.21 | NS* |
| MIa (dB)   | 57.64 ± 3.35 | 64.35 ± 3.11 | *< 0.01 |
| MPa (Hz)   | 2234.92 ± 810.47 | 2233.68 ± 511.99 | NS* |
| GI (dB)    | 54.99 ± 6.11 | 54.53 ± 4.23 | NS* |
| GP (Hz)    | 3008.25 ± 861.84 | 2804.75 ± 629.30 | NS* |

*There was no statistically significant difference

Discussion

This study, for the first time, investigated the correlation between acoustic parameters and masticatory parameters to assess masticatory performance. The sound index, the mastication sound intensity (MI), showed a significant difference between genders in evaluating the masticatory performance, and it was significantly correlated with the critical masticatory parameters in two chewing studies. Moreover, compared to the masticatory parameters, the acoustic parameters showed more accuracy and comprehensiveness during data collection and more convenience in experimental process. This demonstrated that the further study of acoustic parameters evaluating mastication is meaningful.

As shown in Fig. 1, the mean values (± SD) of men were significantly lower than those of women in the comparison of the kinematic parameters of the CC and CF. Meanwhile the mean values (± SD) of D50a showed that the values of men were significantly higher than women. Moreover, in the statistical results of the acoustic parameters, MIa approached compliance with kinematic parameters, and the value for females significantly exceeded that of males.

As in Table 3, Fig. 2 and Additional file 1: Fig. S. 1, Pearson's correlation coefficients showed that MIa was significantly negatively correlated with D50a (r = −0.94), and was significantly positively correlated with CF (r = 0.82), which means that MIa may be a sensitive indicator of masticatory kinematics and degree of mastication. Meanwhile MIa and CC had a low correlation (r = 0.46), indicating that MIa may not be correlated with CC. In the Spearman analysis and the rest of the Pearson's analysis, there were no statistical correlation for any other acoustic parameters (MPa, GP or GI) or masticatory parameters (CC, CTa, CF or D50a).

During the fixed chewing strokes study, descriptive data of masticatory sound, gnathosonic and mastication with every volunteer chewed 4 raw peanuts 21 times are shown in Table 4 and Additional file 1: Table S. 2.

As in Table 5, Fig. 3 and Additional file 1: Fig. S. 2, Pearson's correlation coefficients showed that MIa was significantly negatively correlated with D50a (r = −0.85). In the Spearman analysis and the rest of the Pearson's analysis, there was no statistical correlation for the other acoustic parameters (MIa, GP and GI) and masticatory parameters (CTa, D50a).
mastication sound intensity (MI) indicated the sound energy of the occlusion produced from masticatory movement [41, 42]. Hence, the variation in MI by sex was in accordance with D50a, CF and CC. This result suggested that an indicator of mastication sound intensity (MI) would be valuable in evaluating mastication.

In the following analysis of correlation among acoustic and masticatory parameters, MI revealed that a significant negative correlation existed with D50a (r = -0.94), and a significant positive correlation existed with CF (r = 0.82). In the studies of the masticatory performance with fixed chewing strokes, the test food was in...
accordance with a previous study, and the number of chewing strokes was the average chewing cycle [43]. As shown in the results, in all acoustic parameters, $\text{MI}_b$ was significantly negatively correlated with $D_{50b}$ ($r = -0.85$). As a result, the more strenuous the mastication subjects made, the more energetic the soundwaves and the smaller food the bolus they produced. These results indicated that mastication sound intensity ($\text{MI}$) would be a meaningful indicator of masticatory performance.

Early studies mainly focused on the gnathosonic which is related to occlusal stability and interference [13–16]. To date, the related studies have mainly been based on the classification in occlusal sounds of Watt’s work [44, 45]. Due to limitations of adapterization and analysis methods, the subsequent doubt centralized the methodology, which lacked meaningful data analysis and complete sound capture [20]. Hence, there were few reports about acoustic studies in the stomatology area. The problem was due to the narrow acoustic range of occlusal sound and the deficiency of noise filtering in conventional sound sensors. With the bone-conducted tech which established the independent skeleton path of sound transmission and provided a wider spectrum to annotate the sound data, sound capture could be accomplished without the disturbance of background noise [21, 22].

In the vast majority of studies about gnathosonic and chewing sounds, the indicator analysis was confined to sound frequency and was compared with electromyography. Although the sound frequency was significantly correlated with the value of electromyography, it could not be used to evaluate the mastication process [13–19, 41]. Moreover, previous studies of chewing sound focused on the behavior of chewing and swallowing and the measurement of food texture, rather than investigating masticatory performance [16–18, 42]. Essentially, the sound frequency is more relevant to the vibrational speed of soundwaves than to the vibrational energy [31]. It is easy
to understand that the mastication sound pitch (MP) and gnathosonic pitch (GP) were not correlated with the masticatory parameters. For gnathosonic intensity (GI), it was concluded that the physiological status of normal mastication varies significantly from that of occlusion without food. Furthermore, the gnathosonic intensity (GI) represents the energy of the direct contact of molars, which may be related to the texture of surface of molars and method of occlusion, instead of the status of mastication. In summary, the mastication sound intensity (MI) could be a meaningful indicator to evaluate the masticatory performance.

In addition, we found that, compared with conventional methods, the acoustic parameter data were acquired more accurately and conveniently by annotating the waveform in sound analysis software. The chewing cycle (CC) could be counted synchronously by the emergence of soundwave crests. Meanwhile the chewing time (CT) could be annotated distinctly with the variation of the chewing sound waveform. Furthermore, we could accomplish all of these experiments in a single quiet room without laboratory processing. In summary, the bone-conduction equipment and sound analysis has potential for masticatory studies.

Conclusions
In this research, bone-conduction equipment was used and the occlusal sound signal was further analyzed to study the correlation between acoustic parameters and masticatory parameters. The indicator of mastication sound intensity (MI) was found to have a strong correlation with the state of the food bolus (D50) and chewing frequency (CF) in the entire chewing sequence study. In the study of fixed chewing strokes, the indicator of mastication sound intensity (MI) was highly correlated with the food bolus (D50). The results indicated that the indicator of mastication sound intensity (MI) might be valuable in assessing masticatory performance. The highlight of this research was the application of a bone-conduction tech, which improved the integrity of sound capture and the precision of sound analysis. Furthermore, compared to the complex laboratory procedures of handling food boluses, the measurement of occlusal sounds could be completed by researchers in any quiet places. However, this study merely concentrated on the occlusion of peanuts. Further studies of the occlusal sounds are ongoing to expand the varieties of the test foods and to explore the diverse characteristics of acoustic parameters in different chewing phases. Additionally, we are preparing to establish a masticatory acoustics database of normal people, and to evaluate the mastication of people in different age periods and patients after the dental restoration and treatment of temporomandibular disorder.

Abbreviations
D50: Median particle size; CT: Chewing time; CC: Chewing cycles; CF: Chewing frequency; GP: Gnathosonic pitch; GI: Gnathosonic intensity; MP: Mastication sound pitch; MI: Mastication sound intensity.

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1186/s12903-021-02018-9.

Additional file 1: Table S1. Acoustic and masticatory parameters data of the whole chewing sequence and acoustic parameters data of gnathosonic. Table S2. Acoustic parameters and masticatory parameters data of quantitative test food (peanuts) with fixed chewing strokes (21 times).

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Authors’ contributions
YX contributed to the implementation of the study, data acquisition, design, data acquisition and interpretation, carried out the statistical analysis, and drafted and critically revised the manuscript. LW contributed to the conception and interpretation, drafted the initial report and critically revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analysed during this study are included in this published article (and its supplementary information files).

Declarations
Ethics approval and consent to participate
The experimental protocol was established, according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of Tianjin Stomatology Hospital. Written informed consent was obtained from the participants and their guardians.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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