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# The effect of wearing custom-made mouthguards on the aeroacoustic properties of Japanese sibilant /s/

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**Abstract** – *Background/Aim:* There have been many reports on the discomfort of speech when wearing oral appliances. Fricatives articulated in an oral cavity can be difficult to pronounce when oral appliances are worn, because the oral cavity is partially changed by their installation. Sibilant /s/, one fricative, is especially difficult to pronounce when wearing oral appliances. This study investigates the effect of the difference in the setting positions of the palatal margin of custom-made mouthguards on the aeroacoustic characteristics of sibilant /s/. *Materials and methods:* Eighteen subjects (11 women and seven men) participated. The palatal margin of mouthguards was set at the gingival line for nine subjects and 4 mm from the line for another nine subjects. Acoustical analyses examined the difference of the palatal margins of the mouthguards on the autocorrelation coefficient, the zero crossing count, and the spectral peaks of sibilant /s/. *Results:* The results showed that the zero crossing count of the waveforms and the spectral peaks of sibilant /s/ were significantly broadened and shifted toward the low-frequency range with the mouthguard whose palatal margin extended 4 mm from the gingival line than the mouthguard whose palatal margin was set at the gingival line. *Conclusion:* We believe that a more appropriate palatal mouthguard design for custom-made mouthguards can be made by considering the aeroacoustical effects. Our study supported the mouthguard whose palatal margin was set at the gingival line by considering the influence on pronouncing sibilant /s/. We believe that a more appropriate palatal mouthguard design for custom-made mouthguards can be made based on the balance of aeroacoustical effects and mechanical requirements.

A mouthguard (1, 2), which prevents sports injuries by absorbing sudden impacts in collision sports, is an oral appliance that covers with a soft material the maxillary teeth except for the second molar including the gingival tissues near the teeth margins. The design of custom-made mouthguards, which are fabricated to fit and cover the maxillary teeth except for the second molars (3), has been studied to improve their effectiveness (4) and durability (5). But except for the breathing function, their effect on the general functions of the oral cavity has received little attention (6). When wearing a custom-made mouthguard, speech is difficult because of the thick soft material covering the morphological nature of the anterior oral cavity (7, 8). This discomfort when speaking is one reason why athletes are reluctant to wear them (4, 9). In particular, custom-made mouthguards inhibit the articulation of sibilant /s/ (10). As the articulation of sibilant /s/ is performed palatally to the upper anterior teeth (Fig. 1a), the design of the palatal side shape of custom-made mouthguards exerts a minimal influence on articulation.

The design of the palatal shape of a custom-made mouthguard is not expected to interfere with articulations of sibilant /s/, where the approach of the anterior tongue blade to the anterior palate creates a constriction in the oral cavity called a 'sibilant groove' (11). Sibilant grooves are formed in the back cavity of the anterior teeth at an average of 4 mm long (11–13). The discomfort when pronouncing sibilant /s/ might be caused by inhibiting the aeroacoustic mechanism that produces sibilant /s/ when the mouthguard is inserted. In clinical cases, dentists have tried several positional settings of the mouthguard's palatal margin. For example, the border was placed at the gingival line or 4 mm from it (14, 15). The objective of our study is to show the effect of different setting positions of the palatal margin of mouthguards on the aeroacoustic characteristics of sibilant /s/.

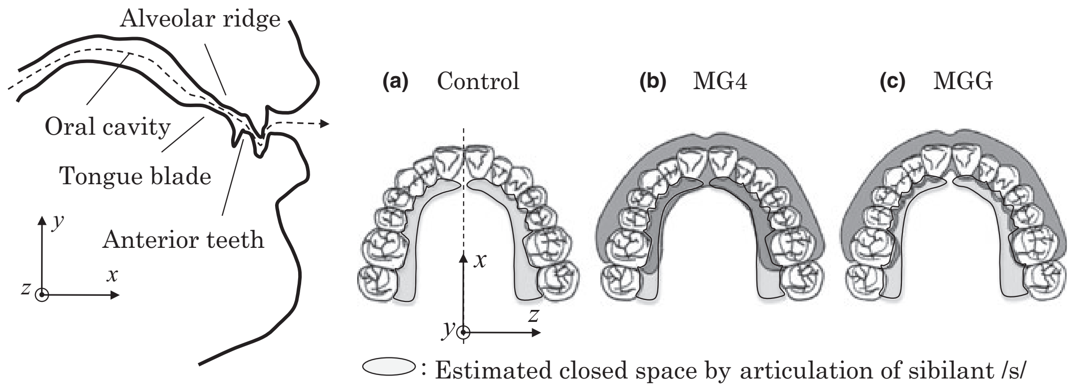


*Fig. 1.* Schematic representation of lateral slice view of oral cavity when sibilant /s/ is produced, and dentition of upper jaw blocked with estimated closed space by articulation of sibilant /s/: (a) normal dentition of Control group, (b) Mouthguard types of MG4 (mouthguard whose palatal margin was extended 4 mm from it) group and (c) MGG (a mouthguard whose palatal margin was set at the normal gingival line) group.

## Materials and methods

### Subjects

Eighteen Osaka University students (11 women and seven men) participated whose ages ranged from 18 to 20 (mean = 19.2 years). All were native speakers of Japanese, and none reported a history of either speech or hearing impairment. None had previously worn a mouthguard. All were informed of the objectives of our study and agreed to participate. They were randomly divided into two groups of nine wearing two different mouthguards (Fig. 1).

### Custom-made mouthguards

Customized single-layer maxillary mouthguards for each plaster dentition model were fabricated using a pressure forming machine (Erkopress, Erkodent, Germany) and 4-mm-thick ethylene vinyl acetate sheets (Erkosoft, Erkodent, Germany). Two kinds of mouthguards were fabricated to compare the voice changes produced by the appliances, because speech smoothness is strongly influenced by the structure of the area of contact between the tongue and the palate. One group (MGG) wore a mouthguard whose palatal margin was set at the gingival line (Fig. 1b), and the other group (MG4) wore a mouthguard whose palatal margin was extended 4 mm from it (Fig. 1c). The reference touch area of the tongue blade on the alveolar ridge articulating sibilant /s/ was mapped in Fig. 1a–c and colored gray (16). The subjects in groups MGG and MG4 were not informed of the existence of the other group or that the designs of the mouthguards were different.

### Speech measurements

Subjects were seated in a quiet room with a microphone (ECM-330; Sony Corp, Tokyo, Japan) 10 cm from their lips oriented at a 45° angle. Each microphone was connected to a preamplifier and an AD converter (UA-30; Roland, Shizuoka, Japan). All utterances were monaurally recorded and digitized at 44 100 samples/s with 16-bit quantization. The Japanese phrase 'usui' (containing an unvoiced sibilant) were first recorded as a control, and then immediately after inserting the mouthguard, they uttered the same sounds five times at 5-s intervals. They made no other utterances during the recording, and a total of six speech-signal data files were stored for each subject. The subjects first produced the Japanese phrase 'usui' without the mouthguard. These speech samples were used as a control (Control) ($N$ = 18). The samples with each mouthguard were divided into two groups of nine: MG4 ($N$ = 45) and MGG ($N$ = 45).

### Aeroacoustic analyses

We estimated the aeroacoustical properties of sibilant /s/ by investigating the characteristics of the power spectra while considering the internal flow and the sound source. Parameterization of the power spectra of the flow-induced sound is generally performed using the dynamic amplitude with the line slopes calculated using the linear regression of the lower (from 500 Hz to the frequency at the peak amplitude) and higher frequencies (from the peak amplitude to 20 000 Hz), where the localized source and the higher source strength are listed as the aeroacoustic effects of sibilant /s/ (Fig. 2) (17). As we consider its aeroacoustic features, the dynamic amplitude with slopes represents the physical characteristics of sibilant /s/ better than other quantification methods.

We measured seven parameters representing the aeroacoustic characteristics of sibilant /s/, which consist of autocorrelation coefficient, zero crossing count, and five spectral properties: $F_{peak}$, $F'_{peak}$, $S_p$, $S'_p$, and $A_d$. The autocorrelation coefficient, which is the correlation between adjacent speech signals, is normally close to zero for unvoiced speech, such as sibilant /s/, although for the voiced speech, it is close to 1 because the speech waveform signals are correlated strongly (18). The zero crossing count indicates the frequency at which the energy is concentrated in the spectrum. Sibilant /s/ is probably produced owing to the oral cavity's excitation

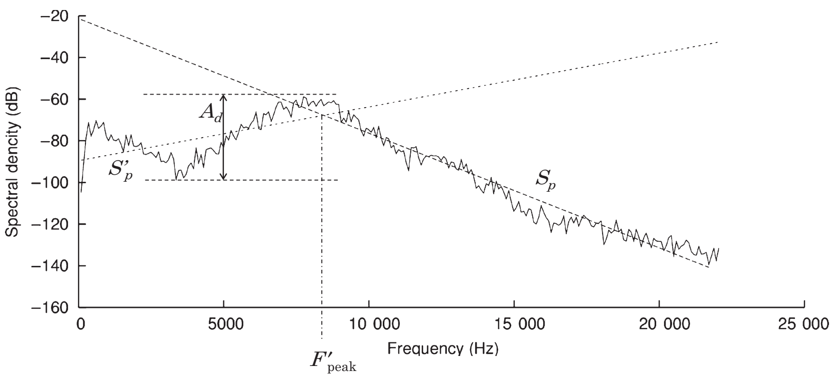


*Fig. 2.* Representative example of power spectra of sibilant /s/. $S_p$ represents the high-frequency range slope (from $F$ to 20 000 Hz), and $S'_p$ the low-frequency range slope (from 500 Hz to the frequency at the peak amplitude). $F'_{peak}$ is the position of an intersection point between the $S_p$ and $S'_p$ lines. $A_d$ is the dynamic amplitude (dB) computed between the maximum amplitude of the power spectra from 500 to 22 050 Hz and the minimum from 500 to 2000 Hz.

by such nonlinear sources as white noise at the point of constriction in its interior and presents a high zero crossing count (19). $F_{peak}$ calculated is a peak of the power spectral density. The low-frequency range slope (from 500 Hz to the frequency at the peak amplitude) $S'_p$ (dB per Hz), and the high-frequency range slope (from to 22 050 Hz) $S_p$ (dB per Hz) were estimated by calculating the linear regression lines with the least squares method. The position of the intersection point $F'_{peak}$ between the $S_p$ and $S'_p$ lines was calculated. Dynamic amplitude $A_d$ (dB) was computed between the maximum amplitude of the power spectral density from 500 to 22 050 Hz and the minimum from 500 to 2000 Hz. The targeted band was changed from 0 to 2700 Hz when it was lower than 500 Hz to avoid peak loss. All signal processing was performed using GNU octave 2.1 (20).

#### Statistical analyses

Concerning the gender effect of the acoustic properties of sibilant /s/ (21), we checked whether it was found and examined the presence of interaction between mouthguard type and gender by conducting a two-way ANOVA with unequal sample size for seven values: autocorrelation coefficient, zero crossing count, $F_{peak}$, $F'_{peak}$, $S_p$, $S'_p$, and $A_d$. As no intersection among them would suggest the effects of each mouthguard on the acoustic properties of sibilant /s/, we performed Tukey's multiple comparisons of means. In this study, we verified the gender effects and focused on MG because we found no interaction between MG and gender, except for $S'_p$. To perform a two-way ANOVA with unequal samples, we used a completely randomized factorial design (CRFpq) conducted by R ver. 2.14 and determined the smallest fixed level at which the null hypothesis can be rejected ($P$-value) to be 5%.

### Results

The autocorrelation coefficient and zero crossing count results computed from the speech waveforms are shown in Fig. 3. As in the two-way ANOVA result with unequal samples for the autocorrelation coefficient, there was no interaction among groups ($P = 0.11$, $F = 2.59$, df = 1, residuals' df = 103), where $P$ is $P$-value, $F$ stands for the proportion between the sample variances in the $F$-test, and df stands for the degree of freedom. The effect of mouthguard type was significant ($P = 3.17 \times 10^{-7}$, $F = 17.37$, df = 2). The result of the Tukey's multiple comparisons of means revealed that the autocorrelation coefficient of the Control group (Fig. 3a) was significantly smaller than the MG4 ($P = 0.006$) and MGG ($P = 3.0 \times 10^{-7}$) groups. The values of the autocorrelation coefficient for the Control group were in reasonable agreement with those found in another study (20). There was no interaction among the groups ($P = 0.11$, $F = 2.53$, df = 1, residuals' df = 103) for the zero crossing count. The effect of the mouthguard type was significant ($P = 9.24 \times 10^{-7}$, $F = 15.95$, df = 2). The result of the Tukey's multiple comparisons of means showed that the zero crossing count of the Control group (Fig. 3b) was significantly higher than the MG4 ($P = 0.04$) and MGG ($P = 1.90 \times 10^{-6}$) groups. Those of the MG4 group were higher than those of the MGG ($P = 7.0 \times 10^{-4}$) group as shown in Fig. 3b.

The power spectra of the speech waveforms recorded from the 18 subjects were also calculated (Fig. 4). The solid line indicates the mean of the temporal ensemble average of the five queues (0.058 ms) of the power spectral density for each group. The dots represent the values of all the queues for each group. Figure 5 gives the

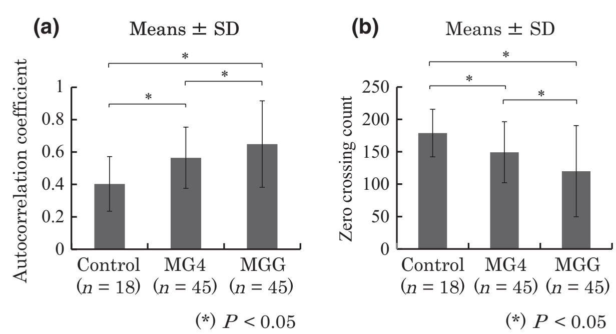


*Fig. 3.* Results of statistical analyses of (a) the autocorrelation coefficient and (b) the zero crossing count.

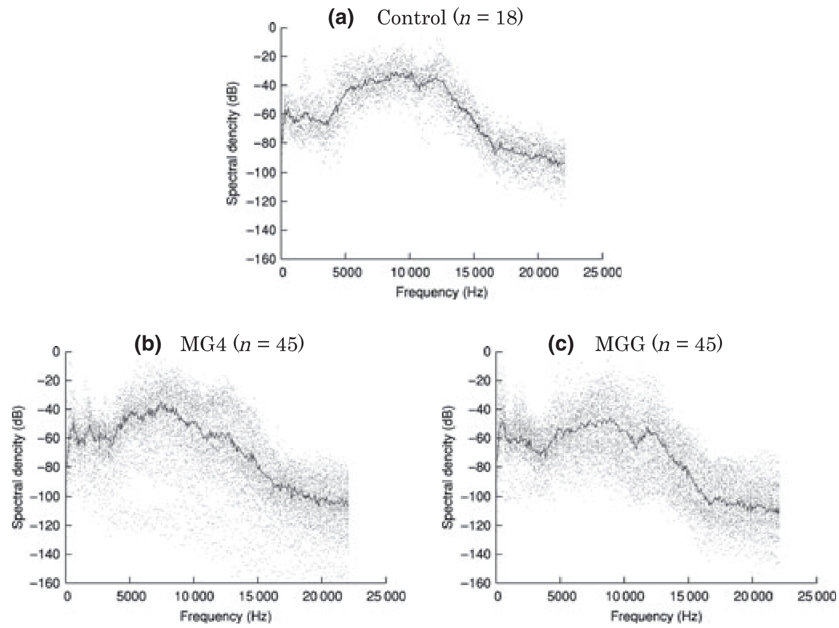


*Fig. 4.* Power spectra of (a) Control, (b) MG4, and (c) MGG groups. The solid line indicates the mean of the temporal ensemble average of the five queues (0.0581 ms) of the power spectra.

statistical profile of Fig. 4, where the five indicators of the power spectra, $F_{peak}$, $F'_{peak}$, $S'_p$, $S_p$, and $A_d$, were computed for each group.

No interaction among groups was found for $F_{peak}$ ($P$ = 0.11, $F$ = 2.66, df = 1, residuals' df = 103). The effect of mouthguard type was significant ($P = 4.43 \times 10^{-7}$, $F$ = 16.92, df = 2). Figure 5a shows that $F_{peak}$ decreased when wearing MGG ($P = 2.3 \times 10^{-6}$) in comparison with those of the Control group, and the value for the MG4 group had a higher frequency than those of the MGG group ($P = 1.2 \times 10^{-4}$). For $F'_{peak}$ ($P$ = 0.19, $F$ = 1.752, df = 1, residuals' df = 103), there was no interaction among groups. The effect of mouthguard type was significant ($P = 1.94 \times 10^{-6}$, $F$ = 14.99, df = 2). $F'_{peak}$ decreased when wearing MGG ($P = 1.97 \times 10^{-5}$) in comparison with those of the Control group, and the value for the MG4 group had a higher frequency than those of the MGG group ($P = 1.07 \times 10^{-4}$).

Figure 5b provides the characteristics of the slopes of the regression lines of the power spectra. There was no interaction among groups ($P$ = 0.25, $F$ = 1.32, df = 1, residuals' df = 103) for the $S_p$. The MGG group's $S_p$, which represents the spectral envelope of noise, became less negative than that of the Control group ($P = 1.43 \times 10^{-5}$), and the value for the MG4 group was less negative than the MGG group ($P = 1.08 \times 10^{-4}$). There was no interaction ($P$ = 0.66, $F$ = 0.19, df = 1, residuals' df = 103) and no significant effects of the mouthguard type ($P$ = 0.13, $F$ = 2.11, df = 1, residuals' df = 103) and gender ($P$ = 0.89, $F$ = 0.02, df = 1, residuals' df = 103) among groups for $S'_p$.

Figure 5c provides the characteristics of dynamic amplitude $A_d$. No interaction among groups was found for $A_d$ ($P$ = 0.09, $F$ = 2.926, df = 1, residuals' df = 103) between the effects of the mouthguard type and gender. $A_d$ decreased when wearing MGG ($P = 4.75 \times 10^{-5}$) in comparison with those of the Control group, and the value of the MG4 group had larger difference between the minimum amplitude of the spectral and the maximum of that than those of the MGG group ($P$ = 0.049).

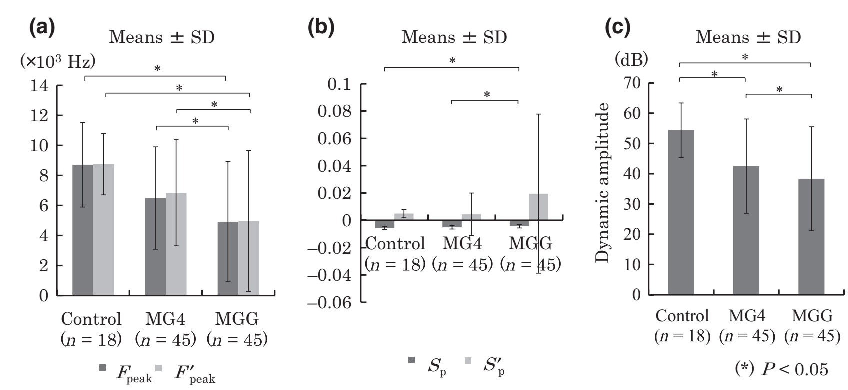


*Fig. 5.* Results from statistical analyses of five power spectra indicators: (a) $F_{peak}$, $F'_{peak}$, (b) $S'_p$, $S_p$, and (c) $A_d$.

## Discussion

The limitation of our technique can be estimated by the number of samples and the range of the effective values. We calculated the effect size of each tested parameter to confirm the reliability of our statistical results. The effect sizes (Cohen's d) (22) of the mouthguard type factor for the autocorrelation coefficient, the zero crossings count, $F_{peak}$, $F'_{peak}$, and $S_p$ were 0.34 ($F$ = 15.95, df = 103), 0.31 ($F$ = 17.27, df = 103), 0.33 ($F$ = 16.92, df = 103), 0.29 ($F$ = 14.99, df = 103), and 0.30 ($F$ = 15.27, df = 103), respectively. Because the effect sizes of every parameter exceeded 0.15 and were $<0.4$, small effects were detected in our statistical analyses.

In this study, the inhibition of different parts of the sibilant groove owing to the MG4 and MGG mouthguards was performed to learn the effect of the palatal shape of the mouthguards on the sibilant /s/ characteristics. The nature of the air flow in the oral cavity when pronouncing sibilant /s/ was forced to change when the mouthguard was worn, because it covered the sharp edges and the apertures of the dentition. Based on Krane (23), simplifying the shape of the flow channel lowers the peak frequency of the aeroacoustic source spectra and broadens the peak width, which might indicate that after wearing a mouthguard, the frequency of the peak of the aeroacoustic source spectra lowered and its width broadened. We assumed that the source spectra peak of sibilant /s/ shifted toward the low-frequency range when wearing MGG, suggesting that the shift toward the low-frequency range changed the morphological complexity when wearing a mouthguard that simplified the oral cavity's morphology. Although MG4 also changed the morphological complexity, no significant difference was found for the spectra peak. On the other hand, the inhibition of the different parts of the sibilant groove between MGG and MG4 probably caused the difference in the frequency of the wave of sibilant /s/. These facts suggest that part of the inhibition of the sibilant groove affected the acoustical characteristics of sibilant /s/.

Our study supported the palatal design of MG4 based on the influence of the mouthguard on pronouncing sibilant /s/, because three important MGG parameters, $F_{peak}$, $F'_{peak}$ and $S_p$, were significantly distorted from those of the Control group. As team sports especially require interactive verbal communication, we recommended MG4. Nevertheless, we must not overlook the effect of the mouthguard's design on its mechanical characteristics for shock absorbance, as a mouthguard's main purpose is injury prevention. Our study presented the effect of the mouthguard on speech that may have been overlooked. For the future, we will find the optimal mouthguard design by balancing mechanical requirements with speech comfort.

## Conclusions

This study presents the effect of different setting positions of the palatal margin of mouthguards on the aeroacoustic characteristics of sibilant /s/. As mouthguards inhibit the constriction when vortexes are generated and change the morphological complexities of the oral cavity, both the unsteadiness and the high frequency of its waveform were significantly modified. Moreover, the spectral peaks shifted toward the low-frequency range owing to the morphological changes occurring in the oral cavity when wearing a mouthguard. These results suggest that aeroacoustical mechanisms should be taken into consideration when fabricating an appropriate palatal design for custom-made mouthguards.

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