Analysis of the Relationship between Palatal Contour and the Phonetic Function in Complete Denture Wearers Using a Speech Recognition System

Tomohiro Ando, DDS, a Masayuki Hideshima, DDS, PhD, a Shusuke Inukai, DDS, a
Yoshimasa Igarashi, DDS, PhD, a and Hiroshi Matsuura, PhD b

a Removable Partial Denture Prosthodontics, Department of Masticatory Function Rehabilitation, Division of Oral Health Sciences, Graduate School of Tokyo Medical and Dental University, Tokyo, Japan
b TOSHIBA Corporation, Corporate Research & Development Center, Tokyo, Japan

Clinical significance
Individuals using dental prosthetic appliances tend to mispronounce the /ʃ/ sound, phonation of which depends on the shape of the palatal contour. Thus, prosthodontists need to create the palatal contour in complete dentures with care. Here, we report that by using a speech recognition system, the palatal contour can be easily adjusted in the waxed denture base.

Abstract
Purpose: This study used a speech recognition system to investigate the intelligibility of the /ʃ/ sound, which is based on the palatal contour of complete dentures.

Methods: Six subjects with an edentulous maxilla participated in the study. The experimental dentures were made of self-curing acrylic resin and four curvatures (0, 2, 4, 6 mm) of the palatal contour were evaluated. A speech recognition program automatically converted the acoustic signals into phonetic segment labels. Labels that correctly recognized the /ʃ/ sound were defined, and the distribution of the correct labels was analyzed in relation to the palatal contour. Palatograms were also recorded to assess tongue movement.

Results: Repeated-measures one-way analysis of variance revealed a significant effect of the curvature of the palatal contour on the appearance ratio of the correct [ʃi] labels (F=53.1, P<0.05). Tukey’s multiple comparisons revealed a significant difference between 0 mm and 2 mm (P<0.001), 0 mm and 4 mm (P<0.001), 2 mm and 6 mm (P<0.001), and 4 mm and 6 mm (P<0.001). Based on the appearance ratios of the [ʃi] labels, the 0 mm curvature of the palatal contour was rated as yielding the highest intelligibility (P<0.01), and based on those of the [ʃi] and [ʒi] labels, the 6 mm curvature was rated as yielding the intelligibility (P<0.01 for both). When tongue movement was assessed from the palatograms, tongue contact was found to be similar to that in the typical palatogram for each recognized syllable.

Conclusion: The curvature of the palatal contour affects the pronunciation of the /ʃ/ sound, and the appropriate curvature of the palatal contour in complete dentures for correct pronunciation of this sound is 2 to 4 mm.

Key words: phonetic function, palatal contour, speech recognition, phonetic segment labels, palatogram

Introduction
Speech is an essential human activity, and the phonetic function in edentulous subjects can be dramatically improved with prosthetic devices; on the other hand, the use of inappropriate dental prostheses can lead to speech problems. It is well known that the /ʃ/ sound tends to be mispronounced. Therefore, the relation between the pronunciation of the /ʃ/ sound and dental prostheses should be clarified.

The three major factors that affect the phonetic function in wearers of complete dentures are the vertical dimension of occlusion, the position of the artificial teeth, and the palatal contour. Most of the literature on phonetic research in the field of prosthodontics until now has focused on positioning of the artificial teeth and the vertical dimension of occlusion. Although some studies have reported a relationship between speech and the curvature of the palatal contour of complete dentures, these studies have focused on the effects on the palatogram and air pressure, and...

not on the sound itself. In addition, although several reports indicate that the palatal contour facilitates pronunciation of the /ʃ/ sound, there is not much evidence on the role of the palatal form in complete dentures with much circumstance. Most of the evidence is only anecdotal, based on the clinical experience of individual dentists. We developed a system to evaluate the phonetic function by using a speech recognition system. Using this system, unlike in traditional methods, the sound itself can be evaluated, and the role of the palatal form in speech production can be investigated in detail.

The purpose of this study was to investigate the changes in the intelligibility of the /ʃ/ sound based on changes of the palatal contour of complete dentures.

Materials and methods

Subjects
Six edentulous patients (1 man and 5 women; age, 49 to 72 years) with satisfactory new maxillary complete dentures treated at the Tokyo Medical and Dental University were recruited as the subjects of this study (Table 1). All the subjects were Japanese and had normal speech and hearing. All the study-related procedures and tests were approved by the Ethical Committee of the Tokyo Medical and Dental University (No. 129). Each subject received a written and verbal description of the study, and informed consent was obtained from each prior to his/her enrollment in the study.

Denture design
The experimental dentures (Fig. 1) were prepared by duplicating the original maxillary dentures using a self-curing acrylic resin (REPAIRSIN, GC Co., Japan). The palatal surface of the experimental denture of each patient was changed using four patterns to analyze the palatal contour: On the midsagittal section, the palatal casts were augmented from the lingual surface of the gingival margin of the incisor teeth by 0, 2, 4, and 6 mm in a direction parallel to the occlusal plane. A magnetic dental attachment (Hyper Slim Cast Molding Keeper Set, J. MORITA Co., Japan) was attached to the denture base to hold the various curvatures of the palatal contour in place during the pronunciation of the study words.

Analysis of the spoken sounds
Analysis focused on the post-alveolar fricative and close front unrounded vowel, [ʃ]. The speech material consisted of a meaningful Japanese word, [ʃiʃiaw], which included the analysis sound with emphasis falling on the second syllable. Each subject was instructed not to pronounce the test word before the recording. The speech of each subject wearing the four palatal plates with varying curvatures of the contour was recorded five times at the subject’s normal rate of speech on the same day. Measurements with the four experimental dentures were made in random order. Each sound was recorded with a head-set type microphone and a laptop computer (PAC9214LDEW, TOSHIBA Co., Japan), and analyzed using the speech recognition program (Fig. 2).

The speech evaluation system (Voice Analyzer, TOSHIBA Corporate Research & Development Center, Japan) uses speech recognition based on 213 types of integrated phonetic segments that represent phoneme and inter-phoneme features. The system performs micro-period evaluations on a frame-by-frame basis and is therefore able to record time-scale information. The system performs macro-period quantitative analysis.
syllable evaluation using the ratio between the numbers of correct and incorrect integrated phonetic segment labels during the period of evaluated syllables.

The flow process of the phonetic function evaluation system is shown in Figure 3. A pattern is extracted from the power spectrum, matched to the phonetic segment of the reference pattern, and the results are labeled and displayed.

The method of extraction of the test sound [ji] from the test word [jiikawa] is shown in Figure 4. The beginning of the [ji] label was the transition from [i] to [ji], and the end was the transition from [ji] to [ka]. Thus, the sections corresponding to [ji] were those between the head transition and the foot transition. Then, the vowel sound of [ji] was removed and the section was defined as the “analysis sound”.

The typical labels are shown in Table 2. The correct labels for [ji] were defined as $$, SS, and $I$. On the other hand, all labels other than those specified above were defined as incorrect labels. The mean appearance ratio of the correct and incorrect labels was computed from five replicated measurements.

**Palatograms**

Palatograms were recorded to assess the tongue movements. The same six edentulous patients, except one (subject E) who went missing for unknown reasons, underwent the recording of the palatograms.

Palatograms were recorded for the test sound [ji] using the test word [jiikawa]. Each patient was tested two times with each of the four palatal plates. The sequence of palatal plates was randomly assigned, and all the recordings were made in a single day.

The experimental dentures were coated with pink alginate impression material (Aroma Fine DFIII Normal Set, GC Co., Japan) and then inserted into the mouths of the subjects. After pronunciation of the test word, the tongue contact areas on the artificial palates were determined by wetting the powder on the denture and assessing the change in color from pink to transparent. Palatograms were obtained using standardized photographs taken with a digital camera (EOS KISS DS6041, CANON Inc., Japan). Photographs of the palatograms were enlarged on print paper, and tracings of the tongue contact areas were...
made. The tracings were then evaluated based on the studies of Yamagata et al.\textsuperscript{12} and Sonoda\textsuperscript{16} (Fig. 5).

The X axis was determined by the distal end of the second molar, and the Y axis was perpendicularly drawn through the midsagittal line of the central incisor teeth. A curve was described by each tooth connecting the cingulum of the anterior teeth and the palatal cusp of the molar teeth. This curve was defined as the external palatal form. The following additional definitions were used: (l) was the distance connecting the right and left side of the basal ridge and the palatal cusp of the molar tooth; (m) was the tongue contact area of the experimental denture on the right side; (n) was the tongue contact area of the experimental denture on the left side. m/l and n/l were measured. These readouts were plotted on a standardized tooth arch.

### Statistical analysis

The primary analysis was to determine the mean appearance ratio of the labels obtained in the five tests done with each per subject. The effect of the four curvatures of the palatal contour on the appearance ratio of the labels was evaluated by repeated-measures one-way analysis of variance (ANOVA) and Tukey’s multiple comparisons for post hoc multiple pairwise comparisons. A statistical software (SPSS for Windows 11.5J, SPSS Japan Inc., Japan) was used for the statistical analyses, and \( P \) values <0.05 were considered to be significant.

### Results

**Speech evaluation system**

The average appearance ratio of the correct labels for \textipa{[jɪ]} for each curvature of the palatal contour is shown in Figure 6. The mean and standard deviation of the appearance ratios of the correct \textipa{[jɪ]} labels increased and decreased, respectively, as the palatal contour was augmented: 39.6±23.9% at 0 mm, 74.9±20.8% at 2 mm, 76.0±16.4% at 4 mm and 43.0±22.9% at 6 mm. Repeated-measures one-way ANOVA indicated a significant effect of the curvature of the palatal contour on the appearance ratios of the correct \textipa{[jɪ]} labels (\( F=53.1, \ P<0.05 \)). Tukey’s multiple comparisons revealed a significant difference between 0 mm

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Classification of correct and incorrect labels of the \textipa{[jɪ]} sound.</th>
</tr>
</thead>
<tbody>
<tr>
<td>phonetic segment</td>
<td>meaning of the phonetic segment</td>
</tr>
<tr>
<td>correct labels</td>
<td></td>
</tr>
<tr>
<td>$$</td>
<td>the continual segment of /$ʃ$/ sound</td>
</tr>
<tr>
<td>SS</td>
<td>the continual segment of /$s$/ sound</td>
</tr>
<tr>
<td>SI</td>
<td>the consonant segment of /$j$/ sound</td>
</tr>
<tr>
<td>incorrect labels</td>
<td></td>
</tr>
<tr>
<td>##</td>
<td>the continual segment of /$ç$/ sound</td>
</tr>
<tr>
<td>CC</td>
<td>the continual segment of /$ʧ$/ sound</td>
</tr>
<tr>
<td>ZZ</td>
<td>the consonant segment of /$ʤ$/ sound</td>
</tr>
<tr>
<td>SY</td>
<td>the consonant segment of /$ɡ$/ sound</td>
</tr>
<tr>
<td>KI</td>
<td>the consonant segment of /$k$/ sound</td>
</tr>
<tr>
<td>GG</td>
<td>the continual segment of /$g$/ sound</td>
</tr>
</tbody>
</table>

Fig. 5 Analysis method of the palatogram: (l), distance connecting the right and left side of the basal ridge and the palatal cusp of the molar tooth; (m), tongue contact area of the experimental denture on the right side; (n), tongue contact area of the experimental denture on the left side. m/l and n/l were measured. These readouts were plotted on a standardized tooth arch.

Fig. 6 Appearance ratios of the correct labels in [jɪ].
Influence of Palatal Contour on the Phonetic Function in Complete Denture Wearers

and 2 mm ($P<0.001$), 0 mm and 4 mm ($P<0.001$), 2 mm and 6 mm ($P<0.001$), and 4 mm and 6 mm ($P<0.001$), however, no significant difference was found between 2 mm and 4 mm ($P=0.997$) or 0 mm and 6 mm ($P=0.923$).

A breakdown of the total incorrect labels is shown in Figure 7.

Based on the appearance ratios of the [çi] labels, the 0 mm curvature of the palatal contour was rated as yielding the highest intelligibility ($P<0.01$), and based on those of the [tı] and [dı] labels, the 6 mm curvature was rated as yielding the intelligibility ($P<0.01$ for both).

Palatogram

The evaluation of the palatograms is shown in Figure 8. The gray areas represent the average palatograms of the five subjects for each curvature of the palatal contour. A continuous line at 0 mm is the standard [çi] palatogram, and the dotted lines at 2, 4, and 6 mm represent the standard [tı] palatograms for normal subjects.

For the palatal plate with 0 mm curvature of the palatal contour, the tongue did not contact the anterior region (from cusp to cusp), and the palatogram had a tendency to show contact in the rear. The space between the tongue and the palate became narrow near the first and second molar, and wider by degrees in front of the first molar. There were close similarities between the palatograms obtained for the 2 mm and 4 mm curvature of the palatal contour: the palatograms neighboring the canines were narrow. For the 6 mm curvature, the palatograms of two of five subjects expressed an arch across the palate, whereas in the remaining three, the front inflection points on either side were nearer than the front inflection points on either side for the 2 and 4 mm curvature.

Discussion

In this study, the phonetic function of denture wearers was evaluated with palatograms and the use of a speech evaluation system. The former method is the traditional way to assess phonetic function, whereas the latter method was developed as a simple and objective method to evaluate phonetic function. Because this system can translate sounds into signals in real-time, sounds can be evaluated simply, rapidly, and objectively, in contrast to other speech tests. In speech frequency research in the past, speech was assessed as right or wrong, and there was scarcely any means to objectively assess what kind of incorrect speech would be recognized in cases with impaired phonetic function. There have been reports about incorrect sounds in the speech intelligibility test, however, the precision of the measurement is not sufficient to provide objective assessment, because of the interference by psychologic auditory factors. The speech evaluation system developed by us, on the other hand, allows correct and incorrect sounds to be recognized objectively.

As for the assessment of the palatograms, in
this study, the palatograms of complete denture wearers were compared with those of normal subjects. Sugiki et al. indicated that the palatogram during the phonation of \[[i]\] in the complete denture wearers exhibited a close approximation to that in normal subjects. This suggested that the palatograms of these subjects could be reliably compared with those of normal subjects, and the average palatograms of our five subjects were analyzed by superimposing the images over the standard palatogram of normal subjects.

Among the four curvatures of the palatal contour, the average appearance ratio of the \[[i]\] labels was significantly increased at 2 and 4 mm. In addition, the palatograms obtained for the 2 and 4 mm curvatures were similar to the standard \[[i]\] palatogram reported by Morita. It is believed that the appropriate curvature of the palatal contour for proper phonation of the /\j/ sound is from 2 to 4 mm. Snow and Allen pointed out that appropriate convexity of the anterior palatal region is important for producing the /\j/ sound. Morikawa et al. stated that, from the perspective of expiratory pressure, 3 to 6 mm was appropriate for phonetic function, and Ito et al. suggested that 2.5 mm was appropriate. The findings of the above studies differed slightly from the results of this study, perhaps because Morikawa et al. used experimental dentures with differences of 3 mm and Ito et al. used experimental dentures with differences of 2.5 mm. However, the results of this study are certainly not inconsistent with those of these other studies. Curvatures of 0 and 6 mm of the palatal contour had a tendency to decrease the average appearance ratio. Thus, it may be concluded that the curvature of the palatal contour in the maxillary denture should be neither too shallow nor too deep for appropriate phonetic function.

The palatograms individualized as below. Palatograms of the 0 mm curvature were the standard /\ç/ sound palatogram alike and a few palatograms of the 6 mm curvature were indicative of plosive sound. Due to the results of incorrect labels and palatogram of 0 and 6 mm, it is believed that in the case of a shallow contour, there is a tendency for the /\ç/ sound to appear, and in the case of a deep contour, there is a tendency for the /\j/ or /\dʒ/ sounds as plosive sounds to appear.

Augmenting the curvature of the maxillary lingual surface of complete dentures from 0 to 6 mm significantly influenced the phonetic function based on our speech evaluation system; the palatograms were also significantly affected. Although the curvature of the palatal contour had a critical impact on the phonetic function, these results indicate that the phonetic function is influenced by the close relationship between speech and tongue movement as well. Additional studies, including conditions with augmented palatal forms, are necessary to confirm this relationship.

There are several limitations to this study. First, the subjects did not undergo speech training with each experimental denture. Ideally, one would need from 1 to 4 weeks to adapt to a new prosthesis. However, the intelligibility of the /\j/ sound has not been shown to improve with an increased length of time wearing new dentures. Thus, we did not think that there was any need to focus on the relationship between the /\j/ sound and adaptation. Second, the position of the maxillary anterior teeth was not evaluated. Most prosthodontists agree that correct placement of artificial teeth gives the best results in terms of correct speech. The tooth position in the dentures could not be evaluated in this study, because the pre-extraction records were not available. However, results showed that when the sounds were made without dentures, the appearance ratio for intelligibility was low, but when the denture was first fitted, the intelligibility of the sounds improved dramatically. Therefore, the tooth position may provide a reasonable estimate of phonetic function. Third, the degree of maxillary anterior ridge resorption was not assessed. Therefore, the results may not be extrapolatable to all patients. Additional studies are needed to determine if the results can be extended to all maxillary edentulous patients.

**Conclusion**

This study suggests that when using a dental prosthetic appliance, the lingual alveolar area to
the incisor should be augmented within a reasonable contour to obtain proper pronunciation of the /ʃ/ sound. Within the limitations of this study, the degree of augmentation of the lingual alveolar area should be from 2 to 4 mm starting at the point of the gingival margin of the incisor teeth in complete dentures. In terms of production of the /ʃ/ sound, if it sounds like /ç/, the contour is shallow, and if it sounds like /tʃ/ or /dʒ/, the contour is too deep.

Acknowledgments: This study was supported by a Grant-in-Aid (No.17592016) from the Ministry of Education, Science and Culture, Japan.

References