INVESTIGATION OF THE ACOUSTIC CHARACTERISTICS OF THE VELUM FOR VOWELS

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ABSTRACT

Results obtained from a previous investigation of the acoustic characteristics of the velum using separate, simultaneous measurements of lip and nostril radiations suggested that nasal radiation was caused by the vibration of the velum. The current study used measurements of intraoral and intranasal sound pressures and velar movements to investigate the acoustic characteristics of the velum during vowel production. To observe changes in the acoustic properties of the velum, the transfer ratio of the section spanning the velum was analyzed and compared for nasalized vowels, non-nasalized vowels and nasal consonants. The results showed that the transfer ratio is larger in closed vowels than it is in open vowels. The effect of the velum vibration on the transfer ratio was observed not only in non-nasalized vowels, but also in nasalized vowels. There is a consistent relationship between the height of the velar position, the transfer ratio and the nasal sound in a vowel section. Specifically, there is a higher velar position and larger transfer ratio and nasal sound for closed vowels, and a lower velar position and smaller transfer ratio and nasal sound for open vowels. The degree of velopharyngeal opening is strongly correlated to the stress position of a sentence. The velopharyngeal port opens more widely in the case of a nasal consonant following a syllable with a stress than it does in other cases.

1. INTRODUCTION

Studies of velar movement have routinely focused on the relatively large displacement observed when the status of the oral/nasal coupling is adjusted for oral/nasal phoneme transitions (Bjork, & Nylen, 1961; Moll, & Shriner, 1967; Moll, & Daniloff, 1971; Kent, Carney, & Severeid, 1974; Kuehn, 1976; Karnell, Linville & Edwards, 1988). More subtle variations in velar movement during speech production have also been described without regard to oral/nasal coupling, usually in relation to the phonetic component of the utterance (Bzoch, 1968; Moll, 1962; Moll, & Daniloff, 1971; Kunsel, 1979).

In order to complete a physiological model of speech production based on the movements of speech organs, it is necessary to determine how the velum interacts with the other speech organs during speech production, and what effect is observed on characteristics of speech sound when the movements of the velum change the coupling degree between the oral and nasal cavities. Moll and Daniloff (1971) used high-speed cinefluorographic films to investigate the timing of velar movements during speech for four normal subjects. They measured velar movement and estimated velopharyngeal opening. The results indicated extensive anticipatory coarticulation of velar movement towards velopharyngeal opening in CVN and CVVN sequences such that velar movement towards velopharyngeal opening began during the approach to the initial vowel in all cases. The authors provided available statistical data on the timing of velar movements.

The acoustic characteristics of the velum have previously been studied by the authors. In those studies (Suzuki, Dang, & Nakai, 1991; Dang, Nakai, & Suzuki, 1993), speech sound was separated into three speech signals radiated from the lips, the nostrils and the pharynx wall. The results showed that a large nasal sound radiated during production of closed vowels and voiced stop consonants, where the velum had been expected to be closed. The sound radiation from the nostrils is considered to be caused by velum vibration.

The basic assumption of this study is that the velum functions during speech not only like a valve, turning on and off the coupling of the nasal cavity to the oral cavity, but also changes its own properties depending on the context to contribute to speech production. The current study has, therefore, focused on both velar movement and changes in the acoustic properties of the velum. For this purpose, sound pressure signals were recorded using three microphones, and movements of speech organs were measured using the x-ray microbeam system. The relationship between the movements and acoustic properties of the velum were investigated based on the measurement data.

2. EQUIPMENT AND APPROACH

In this experiment, sound pressure signals and movements of speech organs were simultaneously recorded. The sound pressures included speech sound radiated from the lips and/or the nostrils, intranasal sound pressure and intraoral sound pressure. The movements of the lips, the jaw, the tongue tip, the tongue body and the velum were recorded using the x-ray microbeam system. Two normal male subjects served in this experiment.

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2.1. X-ray microbeam system and placement of the pellets

This experiment was conducted at the Waisman Center of the University of Wisconsin (Madison, USA). Movements of speech organs were recorded using the x-ray microbeam system of the University of Wisconsin. The x-ray microbeam system is capable of scanning as many as eleven pellets at an aggregate rate of up to 700 times per second. The frequency of repetition for each pellet is specified separately, at rates ranging from 20 to 180 times per second. Details of the system were described in literature (Westbury, 1991). Eleven pellets were used in the experiment, whose positions are shown in Figure 1. The pellet for the measurement of velar movement was stuck on a

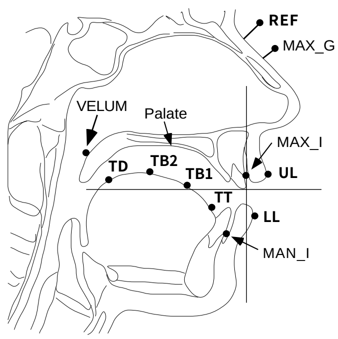

Fig. 1 A sketch of pellet tracking configuration used in the present study.

5-mm-wide tape of soft film with glue, and was placed on the nasal side surface of the velum by passing it through the nasal tract. The position of the pellet on the velum was adjusted by using a flexible endoscope and by x-ray scanning. The scan rate of each pellet is listed in Table 1.

Table 1 Scan rate of each pellet in this experiment (Hz).

Pellet	UL	LL	MAN_I	MAX_I	MAX_G	REF
Rate	20	80	40	40	20	20
Pellet	TT	TB1	TB2	TD	VELUM	
Rate	160	80	80	80	80	

2.2. Setting for sound recording

Three sound pressure signals, speech sound and two intrapressures, were recorded in this experiment. The speech sound was recorded using an EMU-4545 microphone. The two intrapressure signals were recorded using two B&K-4128 microphones with an impedance matching flexible tube which is 1.65 mm in outside diameter, and 0.76 mm in inside diameter. To decrease the effect of velum vibration on the tubes, they were passed through the middle meatus. One of the two tubes was inserted in the velopharynx above the velum. The other one was passed through the velopharyngeal port into the oral cavity. The tube inside the velopharynx was about 8 cm from the nostrils, and the other one inside the oral cavity was about 12.5 cm from the nostrils. The distance between the tips of two tubes was 4.5 cm. The positions of the tubes were confirmed by a flexible endoscope. It was confirmed that the tubes were not filled with mucus from the mucous membrane by monitoring the waveform of the intrapressure signals on a monitor during sound recording. Speech materials are listed in Table 2. They consist of single vowels, syllables with stop and nasal consonants, words and sentences.

Table 2. Speech materials used in this experiment.

1. /a/, /i/, /u/, /e/, /o/.
2. /babababa/,/bibibibi/,/bubububu/, /bebebebe/,/bobobobo/.
3. /dadadada/,/dededede/,/dodododo/.
4. /gagagaga/,/gigigigi/,/gugugugu/, /gegegege/,/gogogogo/.
5. /bapabapa/,/bipibipi/,/bupubupu/, /bepebepe/,/bopobopo/.
6. /datadata/,/detedete/,/dotodoto/.
7. /gakagaka/,/gikigiki/,/gukuguku/, /gekegeke/,/gokogoko/.
8. /ma/,/mi/,/mu/,/me/,/mo/.
9. /am/,/im/,/um/,/em/,/om/.
10. /na/,/ni/,/nu/,/ne/,/no/.
11. /an/,/in/,/un/,/en/,/on/.
12. /aNnai/,/seNsei/,/naNmiN/,/seNdeN/.
13. /zeNzeN/,/suisaNbutsu/,/kiNyobi/.
14. /jiNkeNmoNdai/,/kaNkyomoNdai/.
15. /kurumaouNteNshimasu/.
16. /kurumaokaizoshimasu/.
17. /obaasaNgabyoiNniikimashita/.
18. /obaasaNgabyoshitsuniikimashita/
19. /mainichibeNkyoshimasu/.
20. /mainichireNsyushimasu/.
21. /gohaNwaumai/.
22. /gohaNgamazui/.
23. /seNseikaraeNpitsuomoraimashita/.
24. /seNseikarakudamonoomoraimashita/.

3. RESULTS OF MEASUREMENT

3.1. Position of the velum for vowels

It is known that there are some changes in the position of the velum even for non-nasalized vowels. To investigate the changes of the velum quantitatively, a pellet was placed on the nasal side surface of the velum at a distance of about 9 cm from the nostrils using the method described in Section 2.1. The pellet moved about 1.4 cm vertically and about 0.7 cm horizontally when the velum changed from the resting position to the highest position of closed vowel /i/. The maximum displacement of the pellet during speech was about 1.6 cm from the resting position to the highest position, which was calculated from the vertical and horizontal displacements. To normalize individual difference, a position coefficient, which is a ratio of measured displacement to the maximum possible displacement, was evaluated as a parameter to represent relative displacement of the pellet placed on the velum. For the sake of convenience, the movements of the pellet are referred to as velar movements in the following, though they only represent the movements of one flesh point on the velum.

The position coefficient (P. C.) and relative displacement from the resting position of the velum are shown in Figure 2 for five non-nasalized vowels. The range was calculated from the standard deviation by adding to and subtracting from the position coefficient. The data for the position coefficient are average values of 10 trials for each vowel, which is a single vowel or a vowel in a syllable with a non-nasal consonant. For each trial, the position coefficient was the average value in the vowel section. The results show that the velum is at a higher position in closed vowels, and a lower position in open vowels. The deference between /i/ and /a/ is 0.19 cm in displacement, or 0.12 in position coefficient.

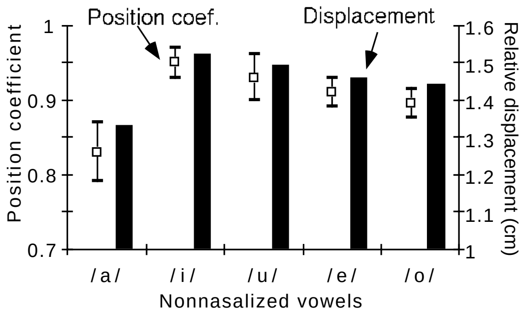

Fig. 2 Position coefficient and relative displacement of the velum in non-nasalized vowels

For vowels following a nasal consonant, referred to as nasalized vowels in the following, an average value can not be used to describe the velar position because it varies with time. The position coefficient at the beginning of a vowel, called the start position coefficient, and the largest position coefficient in a vowel section are used to describe the movement of the velum. The start position coefficient (S. P. C.) and the largest position coefficient (L. P. C.) in a vowel section are given in Table 3. The start P. C.s of the velum in a nasal consonant section, which are in front of the vowels, are also listed in Table 3. There is no significant difference in vowels in the start P. C., except for /a/ which has a smaller P. C. value. The Largest P. C. value of /a/, /i/ and /u/ is 0.03 smaller than their average P. C. value in non-nasalized case. The largest P. C. of /e/ and /o/ reached their average P. C. value in non-nasalized case. The standard deviation of the largest P. C. is smaller than that of the start P. C.. The results for the nasal consonants show that the following vowels cause no significant difference in the start P. C.. /m/ has a higher start P. C. than /n/. One possible explanation for this is that the difference may have been caused by the different postures of /m/ and /n/, though there is the other possibility that some of the deviation may have been caused by individual difference because only two subjects served in this experiment.

Table 3 Position coefficient of the velum for nasalizations

Vowel	/a/	/i/	/u/	/e/	/o/
S. P. C.	0.65	0.75	0.75	0.73	0.75
Std	0.02	0.05	0.04	0.04	0.05
L. P. C.	0.80	0.92	0.90	0.91	0.90
Std	0.00	0.02	0.04	0.01	0.01
S. P. C. of /m/	0.65	0.77	0.75	0.66	0.75
S. P. C. of /n/	0.58	0.59	0.66	0.63	0.64

3.2. Transfer ratio of the velum

In previous studies (Suzuki, Dang & Nakai, 1991; Dang, Nakai & Suzuki, 1993), lip radiation and nostril radiation were separately and simultaneously measured and analyzed. The results showed that nostril radiation is larger in closed vowels than it is in open vowels even for non-nasalized vowels, and the nasal radiation is probably caused by the coupling of the nasal cavity to the oral cavity via vibration of the velum. The results of Section 3.1 show that the velar position changes with vowels. A question here is whether the nasal radiation is correlated to the changes in velar position or not, in other words, whether the changes in velar position affect the properties of velum vibration or not. To investigate the relationship between the acoustic properties and the position of the velum, a transfer ratio of the velum was introduced, which is a ratio of sound pressure levels of intranasal to intraoral cavities, to evaluate changes in acoustic properties of the velum. The intrapressures were taken at two points 4.5 cm apart, located at the nasal side and oral side of the velum. The transfer ratio is illustrated in Figure 3 for non-nasalized vowels and nasalized vowels. For the non-nasalized vowels, the open vowel /a/ and /o/ are 8 dB and 4 dB smaller than the other vowels, respectively. The results show a proportional relationship between the height of velar position, the transfer ratio and the nasal radiation.

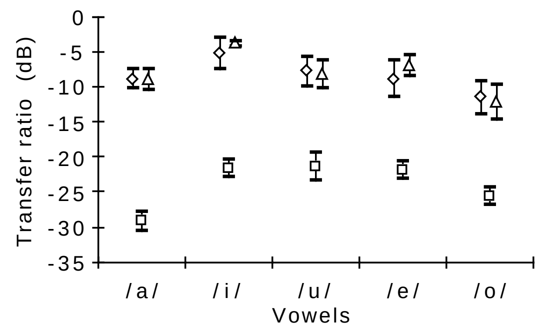

Fig. 3 Transfer ratio of the velum in nasalized and non-nasalized vowels
: Nonnasalized vowels.
: /m/+vowels. : /n/+vowels.

Transfer ratio was an average value in a section of vowel for nasalized vowels, in which amplitude of the sound pressure signals is stable for both intranasal and intraoral pressures. As shown in Figure 3, the transfer ratio is much larger than it is for non-nasalized vowels. However, changes in the transfer ratio of nasalized vowels are almost the same as that of non-nasalized vowels. The transfer ratio of the closed vowel /i/ is the largest of the five vowels, while the ratio of the open vowel /o/ is the smallest. The difference in the transfer ratios between /i/ and /o/ is about 7 dB. The same relationship exists for both nasalized vowels and non-nasalized vowels. Specifically, there is a higher velar position and larger transfer ratio and nasal sound for closed vowels, and a lower velar position and smaller transfer ratio and nasal sound for open vowels.

The transfer ratio shows that more energy transferred from the oral cavity to the nasal cavity for closed vowels. However, the pellet data suggests that velopharyngeal opening is narrower in closed vowels than it is in open vowels, because it is believed that the position coefficient can represent the degree of velopharyngeal opening to some extent when the velum is opening for a production of nasalizations. Observations on nasal consonants also show no significant changes with the following vowels in position and transfer ratio of the velum. To explain this phenomenon, it is hypothesized that the sound component produced by the velum vibration can not be neglected in transferred sound, and that this component is an important source of the difference in the transfer ratio between vowels. This suggests that the velum may have different vibration properties for different vowels.

3.3. Velar movements in sentences

This experiment used sentences, Number 15 to 24 listed in Table 2, as speech material to investigate movements of the velum in connected speech. The speech rate was 4-6 syllables per second. Figure 4 shows an example of the position coefficient and sound pressures in the sentence /gohaNwaumai/. As shown in Figure 4, there are two valleys in the velar movement pattern, one for each nasal consonant. For the nasal consonant /N/, velar movement towards velopharyngeal opening begins at about middle of vowel /o/, with the largest opening at the end of vowel /a/ in front of /N/. For the nasal consonant /m/, velar movement towards velopharyngeal opening begins at the beginning of vowel /u/, which is in front of /m/, with the largest opening near the end of /u/ and the beginning of /m/. Nasal consonants show a strong effect on the vowels in front of and behind them. The effect, however, declines rapidly on the vowels when spanning a vowel. In the vowel /a/ between sequences /Nw/ and /um/, for example, the position coefficient is close to that of non-nasalized /a/.

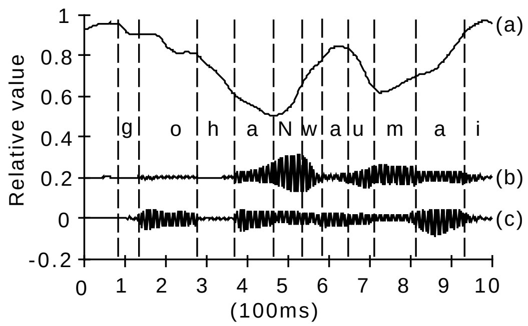

Fig. 4 The position coefficient and sound pressures in the sentence /gohaNwaumai/.
(a) The position coefficient of the velum.
(b) The intranasal sound pressure.
(c) The speech sound.

After analyzing the speech material of the sentences, the following results were obtained. 1). There is one valley in the velar movement pattern for each VN(N)V sequence. Velar movement towards velopharyngeal opening usually begins during the approach to the initial vowel, with the maximum opening occurring at the end of the initial vowels. Velar movement towards closure begins at the beginning of the nasal consonant. 2). In a NVN sequence, the velar movement towards closure usually begins at the beginning of the initial nasal consonant. The maximum closure occurs at a position about 1/3 of a vowel section from the beginning of the vowel, and the maximum position coefficient is about 0.3 smaller than that in the non-nasalized case of the vowel. In an NV1V2V3N sequence, the maximum position coefficient in the V2 section is about 0.1 smaller than that in the non-nasalized case of the vowel. 3). The largest pharyngeal opening in a sentence occurs in a nasal consonant, where the nasal consonant is close to the stress of the sentence. In this case, the minimum position coefficient is about 0.45-0.55. In the other cases, the minimum position coefficient in velopharyngeal opening is about 0.55-0.70. 4). There is no significant change in the degree of the maximum velopharyngeal opening for the nasal consonant close to the stress when the speech rate increases, though the degree of the maximum opening usually decreases for a nasal consonant without a tress when the speech rate increases.

4. CONCLUSION

Using the transfer ratio and the position coefficient which are introduced in this paper, the relationship between the acoustic characteristics and relative displacement was investigated for V, CV and NV. The transfer ratio showed that more energy transfers from the oral cavity to nasal cavity for closed vowels, though the pellet data suggests that velopharyngeal opening is narrower in closed vowels than it is in open vowels. This suggests that the velum may have different vibration properties for different vowels, and that the vibration properties cause differences in the transfer ratio of the velum. The results support our assumption described in the section of Introduction.

The timing of the velar movements was not given in detail in this paper because the results of timing in sequences were almost similar to that obtained by Moll & Daniloff (1971). This study focused mainly on the changes in the amount of velar movements for different vowels. The data on velar movements in sentences showed that the extent of velar movements is different for different vowels even in the same context sequence. The extent of velar movements in vowels, however, can be predicted by velar positions for non-nasalized vowels. The maximum and minimum values of velar movements in a sequence can be obtained with reference to the value in the non-nasalized case of the same kind of vowels. The timing of velar movements can be evaluated using the "look ahead" mechanism according to a specified sequence. The results on the amount of velar displacement would be available to build a physiological model with velar movements.

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