CHIBA AND KAJIYAMA MEASURED 3D CONFIGURATIONS OF THE HUMAN VOCAL TRACT AND MADE PHYSICAL MODELS BASED ON THE MEASUREMENTS

Takayuki Arai
Sophia University, Japan
arai@sophia.ac.jp

Abstract: In 1930's, Chiba and Kajiyama conducted 3D measurements of the human vocal tract for the first time in history. In this paper, we first reviewed how they measured vocal-tract configurations. They further simplified the vocal-tract configurations and made physical straight models based on the simplifications. In addition to introducing our replicas of the straight models based on their simplifications, we also designed bent models based on their 3D measurements.

1 Introduction
Chiba and Kajiyama published "The Vowel, Its Nature and Structure" in 1941-42 [1]. This book is considered as one of the classics in the modern speech science, because this book integrated the mechanisms of vowel production and perception from the viewpoints of physiology, physics and psychology in a single book [2,3]. In this book, they first analyzed the voice source in Part 1. In Part 2, they applied Fourier analysis to obtain vowel spectra and discussed the theory of simple resonators, their equivalent electric networks, and basic aspects of vocal tract configuration. In Part 3, they measured vocal tract configurations by using X-ray photography, palatography, and laryngoscopic observation of the pharynx [4]. Then, they calculated the spectra from the cross-sectional area functions of vowels [2]. They even computed the distribution of volume and particle velocities in each vocal tract. Finally, they discussed human perception of vowels in Part 4. Around 1950, Kenneth N. Stevens came across The Vowel at MIT [5]. When Gunnar Fant visited MIT, he encountered The Vowel, as well. Chiba and Kajiyama viewed the mechanisms of vowel production from phonation and articulation [3]. This view merged with the filter theory and lead to the Fant's source-filter theory [6]. It also helped him to process X-ray data of Russian speech sounds [6].

In this paper, we first review how Chiba and Kajiyama conducted 3D measurements of the vocal-tract configurations. Then, our replicas of the straight models based on the their simplifications of the measurements are introduced. Finally, we design bent models based on their 3D measurements.

2 3D measurement of the vocal tract configurations
Chiba and Kajiyama used the most advanced technologies at the time including the X-ray imaging device, combined with palatography and laryngoscopic observation of the pharynx, and measured the 3D vocal tract configurations.

2.1 Plane vs. solid palatograms
After pronunciation, a palate with powder shows a pattern of regions where the tongue has touched against the palate. Chiba and Kajiyama called it as "plane palatograms." They also claimed that this kind of palatograms shows heavy variability due to the speaker individuality. Therefore, they made "solid" palatograms, instead.

Figure 1 shows two artificial palates: positive and negative. Figure 2 shows cross-sections of negative artificial palate. They were used to estimate the configuration of the oral cavity.
Figure 1. Two artificial palates: positive and negative (from Fig. 62, Chiba and Kajiyama [1]).

Figure 2. Cross-sections of negative artificial palate (from Fig. 63, Chiba and Kajiyama [1]).

Figure 3. One of the pictures of "Old Phonetics Lab." at the Tokyo School of Foreign Languages (from the archive at the Phonetics Laboratory, Sophia University).
2.2 X-ray imaging

The X-ray imaging device used in *The Vowel* was one of the most state-of-the-art models at that time and made by Shimadu. Figure 3 shows a picture of "Old Phonetics Lab." at the Tokyo School of Foreign Languages, where Chiba and Kajiyama conducted experiments for *The Vowel* from 1934 through 1939.

**Figure 4.** Left: sections of vocal tract of Japanese vowels /i/. Right: simplified dimensions for vowel /i/. (Figs. 68 and 69, Chiba and Kajiyama [1]).

**Figure 5.** Left: sections of vocal tract of Japanese vowels /a/. Right: simplified dimensions for vowel /a/. (Figs. 68 and 69, Chiba and Kajiyama [1]).
2.3 Sections of vocal tract
Figures 4 and 5 are Figures 68, 69, 72 and 73 in *The Vowel*. The left panels in Figures 4 and 5 show sections of vocal tract of Japanese vowels /i/ and /a/ obtained from the combination of X-ray photography, palatography, and laryngoscopic observation of the pharynx. The right panels in Figures 4 and 5 are the simplified dimensions for these two vowels.

3 Physical models of the human vocal tract

3.1 Replicas of the straight models
In 2001, we celebrated the 60th anniversary of the publication of *The Vowel* and replicated Chiba and Kajiyama's straight models originally described in their book [7]. Starting from page 128, there is a section of "Artificial Vowels" with description of their physical models being able to produce vowels resembling to natural sounds [1]. Figure 6 shows the replicas of the straight models. In Arai [7], we also demonstrated that the physical models of the human vocal tract is very useful and effective for education in speech science and acoustic phonetics. Please see [8,9,10] for further discussions.

![Figure 6. Replicas of Chiba and Kajiyama's straight models (from left, /i/, /e/, /a/, /o/ and /u/).](image)

![Figure 7. Newly designed bent model for vowel /i/ based on the 3D measurements in The Vowel [1].](image)
3.2 Designing bent models based on the 3D measurements

In this paper, we further designed bent models based on the 3D measurements by Chiba and Kajiyama. Figures 7 and 8 show the designs of vowels /i/ and /a/ by combining dimensions in Figures 4 and 5, respectively. Although Chiba and Kajiyama drew outlines of the uvula, epiglottis, and piriform fossa, we omitted them for the designs in these figures.

4 Summary

In this paper, we first reviewed *The Vowel* by Chiba and Kajiyama including how they measured configurations of the human vocal tract. Their simplifications of the measured vocal-tract configurations were also reviewed. Not only our early replicas of the straight models based on their simplifications were introduced, but bent models based on their original 3D measurements were newly designed. These days, computer models are widely available, and we know they are useful in pedagogical settings as well. However, we also showed that producing vowels through physical models is intuitive and still educational for all ages. Newly proposed physical models are more realistic because they are bent and towards simple anatomy. Thus, both straight and bent simple models are useful depending on how we use them for educational purposes, and we still benefit from *The Vowel* by Chiba and Kajiyama, after more than 75 years of its publication.

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