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Quantification of vocal tract configuration of laryngectomees by acoustic reflection technology (ART)

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Abstract

This study compared the vocal tract configuration, including the length and volume, of alaryngeal and laryngeal speakers. Thirty alaryngeal speakers and 30 laryngeal speakers were recruited for the study. Pharyngometry, which is an acoustic reflection technology (ART), was used to measure the vocal tract parameters of the participants. Results showed that there was no significant difference in the length and volume of the vocal tract of the alaryngeal and laryngeal speakers. The finding suggested that the difference in the formant frequency during vowel production by alaryngeal and laryngeal speakers may be due to factors other than vocal tract configuration. The finding also suggested that the independence of the source and the filter (Fant, 1960; Pickett, 1999) may not be applicable to alaryngeal speakers.

Introduction

Total laryngectomy involves the surgical removal of a pathological larynx, usually for patients with terminal laryngeal cancer, especially after chemo- or radiotherapy fails to work. During the surgery, the entire laryngeal mechanism including the vocal folds, the laryngeal soft tissues, and sometimes even the hyoid bone will be removed. After total laryngectomy, patients lose their ability to phonate. According to the source-filter theory, all speech sounds are produced with a sound source (vocal folds) and a filter (vocal tract) (Pickett, 1999). With the vocal tract usually retained, the laryngectomees need to learn to speak with an alternative phonation method using a replacement sound source in order to regain verbal communication. The four types of alaryngeal speech currently available to alaryngeal speakers in Hong Kong include the standard esophageal (SE), tracheoesophageal (TE), electrolaryngeal (EL) and pneumatic artificial (PA) speech (Ng, Kwok, & Chow, 1997).

The source-filter theory assumes the independence relationship between laryngeal sound source and supralaryngeal filter (Fant, 1960; Pickett, 1999). Removal of vocal folds during total laryngectomy should, in theory, not cause any change to the resonance characteristics of the vocal tract. As vocal tract's filtering property can be acoustically reflected by the formant pattern associated with the vowels being produced (Johnson, 2003), it follows that alaryngeal speakers should exhibit similar vowel format patterns as laryngeal speakers, despite the use of a new sound source for phonation. A number of studies have documented findings that support this notion. Keazi et al. (2007) investigated the formant frequncies in alaryngeal and laryngeal speakers, and reported similar formant frequencies in female alaryngeal and laryngeal speakers, although signifcant difference was found for the male speakers. Luchsinger (1952, p. 143 as cited in Van As, van Ravensteijn, van Beinum, Hilgers, & Pols, 1997) reported little difference in the formant frequencies produced by laryngeal and superior esophageal speakers.

However, a review of the literature revealed other studies reported contradictory findings. Ng and Liu (2009) investigated the vowels produced by Mandarin esophageal speakers and found significantly higher formant frequencies in esophageal than laryngeal speakers of Mandarin. Ng and Chu (2009) compared the Cantonese vowels of alaryngeal and laryngeal speakers by using spectral analysis, and reported significantly higher formant frequencies in alaryngeal speakers. Similar findings were also reported in a study of Spanish vowels produced by alaryngeal speakers (Cervera, Miralles, & González-À lvarez, 2001). Alaryngeal speakers were associated with higher formant frequencies, indicating a shortened vocal tract post-operatively . According the above discussion, studies appear to suggest a discrepancy in vocal tract filter configuration between alaryngeal and laryngeal speakers. It follows that there is a lack of independence between the laryngeal source and the supralaryngeal filter.

That said, vocal tract configuration of alaryngeal speakers was studied only to a limited extent, possibly due to technological limitations. Diedrich and Youngstrom (1966) investigated the vocal tract length of a patient before and after laryngectomy by using cinefluoroscopy and found shortened vocal tract post-operatively. Koo et al. (1998) studied vocal tract length of alaryngeal and laryngeal speakers using magnetic resonance imaging (MRI) during the production of Korean vowels. They found shorter but insignificant vocal tract length in alaryngeal speakers when compared with laryngeal speakers.

Yet, the existence of potential radioactive hazard associated with cinerfluoroscopic studies greatly limited further research of vocal tract configuration pre and post laryngectomy. MRI studies, on the other hand, are also restricted because of its high cost, long operation time, and potential danger due to the effect of powerful magnetic field on any ferromegnetic metal present on the patient. In order to confirm the lack of independence between laryngeal source and supralaryngeal filter, the present study aimed to reveal whether there is difference in vocal tract configuration between alaryngeal and laryngeal speakers by using Acoustic Reflection Technology (ART). Also known as pharyngometry, ART is an advanced technology that makes use of acoustic echoes to derive the relevant volumetric information including length, cross-sectional area, and volume of the vocal tract. It delineates the vocal tract configuration, from the incisors to the glottis, as an area-distance curve, which allows us to obtain volumetric information of different sections of the vocal tract separately. Compared to cinefluoroscopy and MRI, ART is non-invasive, fast, radiation-free and it requires little cooperation from the subject (Kamal, 2004). It has been commonly used in measuring airway of children and adults who suffer from obstructive sleep apnea (OSA) (Gelardi et al., 2007; Gozal & Burnside, 2004; Kamal, 2004). A number of studies (Jung, Cho, Grunstein, & Yee, 2004; Kamal, 2004; Viviano, 2002) have demonstrated the reliability and validity of pharyngometry in quantifying the airway of individuals with OSA as well as healthy individuals.

As mentioned previously, a large number of studies revealed significant difference in vowel formants associated with alaryngeal and laryngeal speakers (Cervera et al., 2001; Liu & Ng, 2009; Ng & Chu, 2009), with alaryngeal speakers consistently demonstrated higher first and the second formants than laryngeal speakers. As formant frequency is generally inversely proportional to vocal tract length (Fant, 1960), it was hypothesized that the vocal tract is shortened after laryngectomy, leading to elevated formant values. To date, only limited research directly provided objective and first-hand measurements of the vocal tract of laryngectomees (Diedrich & Youngstrom, 1966; Koo et al., 1998). Numeric data describing vocal tract configuration after laryngectomy are scarce. Others relied on indirect measures such as formant frequencies (Cervera et al., 2001; Liu & Ng, 2009;

Ng & Chu, 2009). In the attempt to verify the hypothesis, the present study compared volumetric data of vocal tracts of alaryngeal and laryngeal speakers, including vocal tract length, cross-sectional area and volume data.

To further our understanding of alaryngeal speech production post-laryngectomy, the present study aimed to: (1) quantify vocal tract configuration of alaryngeal speakers; (2) verify the assumption of the source-filter theory - the independence relationship between larygeal source and supralaryngeal vocal tract; and (3) confirm the hypothesis that the vocal tract of alaryngeal speakers is shorter than that of laryngeal speakers.

Methods

Participants

Thirty male alaryngeal speakers of Cantonese were recruited from the New Voice Club of Hong Kong. The age range of the participants was between 50-90 years old. Thirty age-matched male laryngeal speakers were also recruited from two local Neighborhood Elderly Centres and served as the controls. All participants were screened using a tailor-made questionnaire and the selection criteria included the absence of hearing impairment, upper respiratory infections, as well as neurological and respiratory system abnormalities except those related to laryngectomy for the alaryngeal speakers. The demographic information of the participants is summarized in Table 1. Mann Whitney U tests showed no significant differences in the age [U = 375, p = -1.000], height [U = 380, p = -1.140] and weight [U = 377, p = -1.009] between the alaryngeal and laryngeal group.

Table 1. Mean, standard deviations, range of age, height and weight of participants and statistical results of the alaryngeal and laryngeal groups.

		Alaryngeal speakers (n=30)	Laryngeal speakers (n=30)	U	p
Age (years)	Mean	69.5	69.7	U = 375	-1.000
	SD	10.47	10.17		
	Range	50-89	50-89		
Height (cm)	Mean	170.87	170.47	U = 380	-1.140
	SD	5.41	6.83		
	Range	160-181	159-183		
Weight (kg)	Mean	71.87	69.20	U = 377	-1.009
	SD	8.27	9.94		
	Range	56-86	53-86		

Instrumentation

An Eccovision Acoustic Pharyngometer (Hood Laboratories, USA) was used to measure vocal tract configuration of the participants. The apparatus consists of a wavetube for generating and receiving acoustic pulses, a microcomputer for converting the analog signal transmitted from the wavetube to digital signal and a monitor for real-time display of the volumetric information. When taking a measurement, short audible acoustic pulses were emitted by a generator and the acoustic energy was transmitted to the vocal tract of the participant through a disposable mouthpiece. For laryngeal speakers, the acoustic pulse travels from the oral cavity to the glottis at the vocal folds. As the alaryngeal speakers had their vocal folds removed and trachea detached from the esophagus, the acoustic wave would travel to the pharyngoesophageal (PE) segment at the end of hypopharynx instead of the glottis for the alaryngeal speakers. As the acoustic pulse travels along the vocal tract, the sensor of the wavetube detects the acoustic energy that is reflected back to the wavetube at points of constriction, for example, at the oral-pharyngeal junction (OPJ) at the uvula, at the PE segment for alaryngeal speakers and at the glottis for laryngeal speakers. The reflected acoustic energy is then recorded and the volumetric information was analyzed from the arrival time and amplitude of the reflected signal. A graph, named pharyngogram, with the cross-sectional area against the distance along the vocal tract to the glottis (or PE segment for alaryngeal speakers) is then plotted and displayed.

Procedures

During the ART measurement, the participant sat upright, with the wavetube, held by the clinician and parallel to the floor, placed at the mouth of the participant through a sterilized mouthpiece to prevent sound leakage during the measurement. The participant was then instructed to produce the vowel /a/ silently to achieve a stable and neutral position of the tongue. A total of four measurements were taken. The first measurement required the participant to hold his/her breath. The purpose of taking this measurement was to locate the position of OPJ, which is defined as the boundary between the oral and pharyngeal cavities, on the pharyngogram for reference for later analyses. When the participant stopped the breathing, the velopharyngeal (VP) port was opened, leading to the narrowing of the OPJ. The decrease in the cross-sectional area at the OPJ would help identify the location of OPJ on the pharyngogram as shown as a trough. The remaining three measurements were used for analysis of vocal tract configuration. The participant was guided to slowly breathe through the mouth. The purpose of maintaining mouth breathing was to ensure the closure of the VP port, preventing inclusion of the nasal cavity in the measurement (Gelardi et al., 2007). For alaryngeal speakers, as mouth-breathing cannot be achieved due to the detachment of the trachea from the pharynx, the participants were asked to imitate the action mentally. Depending on the extent that the position of OPJ on the pharyngogram matched with that in the first measurement, one of the three measurements was chosen for analysis.

Data analysis

In the present study, six volumetric parameters of the vocal tract between the alaryngeal and laryngeal group, including the length (in centimeters) and the volume (in milliliters) of the oral cavity, the pharyngeal cavity and the whole vocal tract were obtained. The section of vocal tract analyzed was selected manually on the pharyngogram displayed on the screen of the pharyngometer. After the appropriate sections were marked, the system automatically generated the distance and volume data of the corresponding section. According to the operation manual of the pharyngometer (E. Benson Hood Laboratories, 1998), the section representing the oral cavity starts from the incisor (at the distance 0.0 cm) and ends at the trough representing the OPJ, while that of the pharyngeal cavity starts at the OPJ and ends at trough corresponding to the PE segment and the glottis for alaryngeal and laryngeal speakers respectively.

The mean and standard deviation of the length and volume of the oral cavity, the pharyngeal cavity and the whole vocal tract for alaryngeal and laryngeal speakers were calculated. Normality and homogeneity were tested at a significance level of 0.05 for each volumetric measurement for the alaryngeal and laryngeal groups. Each of the six outcome measures were compared between the alaryngeal and laryngeal group of speakers by using independent samples t-tests or Mann Whitney U tests using a preset significance level of 0.05. To ensure reliability, each vocal tract dimensional data was re-analyzed by the same investigator and a second examiner. The inter- and intra-examiner reliability were analyzed by using Spearman *rho* preset at a significance level of 0.05.

Results

The mean and standard deviation values of the six vocal tract configuration parameters, including length and volume of oral cavity, pharyngeal cavity and the entire vocal tract, are presented in Table 2. As normality was lacking (according to results of Shapiro-Wilk test) for oral length, pharyngeal length and pharyngeal volume of both the alaryngeal and laryngeal groups, Mann-Whitney U tests were carried out. Independent-samples *t*-tests were used for the remaining parameters, namely oral volume, total length and total volume. Statistical results are summarized in Table 2. According to Table 2, no significant difference was found for all vocal tract parameters between the alaryngeal and laryngeal groups. Though not statistically significant, the alaryngeal speakers seemed to have longer oral length and larger oral volume, but shorter length and smaller volume of the pharyngeal cavity and the entire vocal tract than the laryngeal group (see Figures 1 and 2).

Table 2. Means, and standard deviation values, and statistical results of vocal tract parameters for alaryngeal and laryngeal speakers.

		Alaryngeal speakers		Laryngeal speakers		*T* or *U*	*p*
		Mean	SD	Mean	SD		
Oral cavity	Length (cm)	9.5	1.76	9.3	1.42	*U* = 382.0	-1.014
	Volume (ml)	50.3	12.33	48.1	11.77	*t*(58) = 0.708	0.482
Pharyngeal cavity	Length (cm)	8.6	1.65	9.1	2.17	*U* = 382.5	-1.000
	Volume (ml)	22.4	9.34	25.3	11.23	*U* = 373.0	-1.138
Entire vocal tract	Length (cm)	18.2	1.44	18.4	1.44	*t*(58) = -0.568	0.572
	Volume (ml)	72.7	13.41	73.4	13.79	*t*(58) = -0.189	0.851

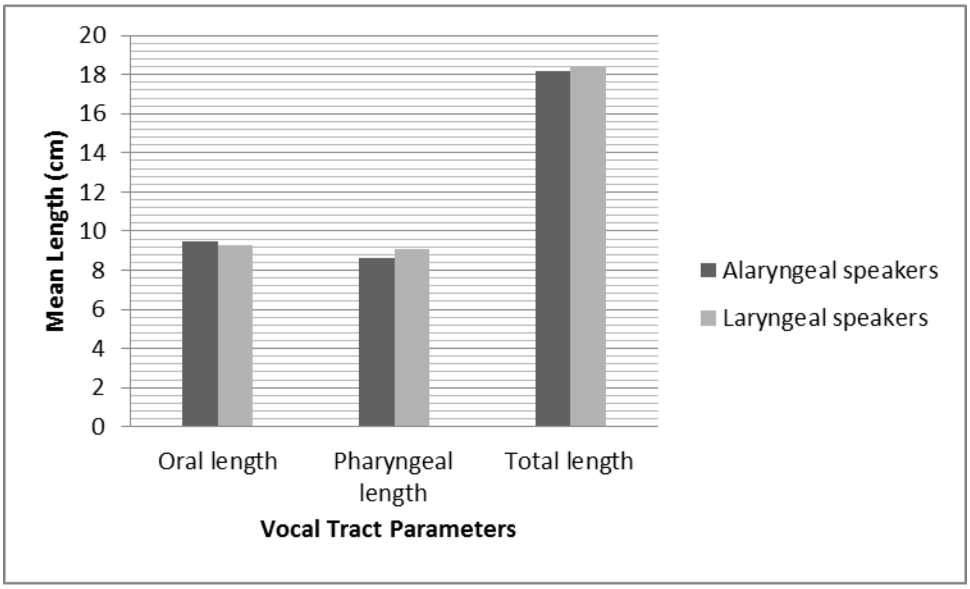

Figure 1. Mean oral length, pharyngeal length and total vocal tract length of alaryngeal and laryngeal speakers.

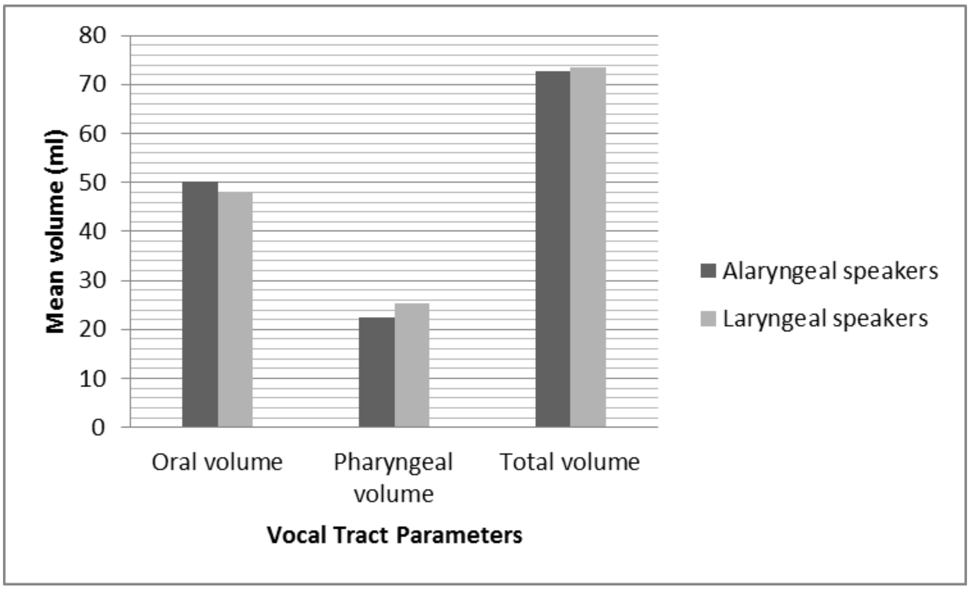

Figure 2. Mean oral volume, pharyngeal volume and total vocal tract volume of alaryngeal and laryngeal speakers.

Inter-rater and intra-rater correlation coefficients for the six vocal tract parameters for both the alaryngeal and laryngeal group are summarized in Tables 3.

Significant correlation ($p < 0.01$) was obtained for all the analysis.

Table 3. Inter- and intra-rater reliability coefficient for vocal tract parameters of the alaryngeal and laryngeal group.

Inter-rater reliability					
		Alaryngeal speakers		Laryngeal speakers	
		Spearman's *rho*	*p*	Spearman's *rho*	*p*
Oral cavity	Length (cm)	0.715	0.000	9.3	1.42
	Volume (ml)	0.702	0.000	48.1	11.77
Pharyngeal cavity	Length (cm)	0.496	0.005	9.1	2.17
	Volume (ml)	0.782	0.000	25.3	11.23
Entire vocal tract	Length (cm)	0.766	0.000	18.4	1.44
	Volume (ml)	0.547	0.002	73.4	13.79
Intra-rater reliability					
		Alaryngeal speakers		Laryngeal speakers	
		Spearman's *rho*	*p*	Spearman's *rho*	*p*
Oral cavity	Length (cm)	0.934	0.000	0.784	0.000
	Volume (ml)	0.795	0.000	0.877	0.000
Pharyngeal cavity	Length (cm)	0.784	0.000	0.812	0.000
	Volume (ml)	0.892	0.000	0.887	0.000
Entire vocal tract	Length (cm)	0.771	0.000	0.878	0.000
	Volume (ml)	0.878	0.000	0.912	0.000

Discussion

The present study investigated the possible effect of total laryngectomy on the vocal tract volumetric configuration, by establishing direct rudimentary data on the vocal tract configuration of alaryngeal speakers (see Table 2). No significant difference in the vocal tract parameters of the alaryngeal and laryngeal speakers, including the length and volume measures of the oral cavity, pharyngeal cavity and the entire vocal tract, was reviewed. Such finding might shed light on the independence of the source and filter in the source-filter theory and the verification of the hypothesis that vocal tract of alaryngeal speakers is shorter than that of laryngeal speakers.

A large number of studies consistently showed that the formant pattern in vowel production was different between alaryngeal and laryngeal speakers (Cervera et al., 2001; Liu & Ng, 2009; Ng & Chu, 2009). As the filtering properties of the vocal tract can be reflected by the formant frequencies in vowel production (Johnson, 2003), these findings have led to a hypothesis that the vocal tract configuration of alaryngeal and laryngeal speakers are different. This hypothesis is commonly considered true because, in theory, the surgical procedure of total laryngectomy greatly alters the head and neck anatomy by, for example, removing the hyoid bone together with the larynx and attaching the end of hypopharynx to the upper esophagus (Evans, 1990). However, this study revealed results that appear contradictory to the hypothesis. The vocal tract length and volume of alaryngeal and laryngeal speakers did not differ significantly.

Based on the findings, it is suggested that there may be contributing factors other than vocal tract configuration explaining the difference in formant frequencies associated with the two speaker groups. One contributing factor may be related to the inherent difference of the phonatory mechanism between alaryngeal and laryngeal speech production. There are four common types of alaryngeal speech, including the

SE, TE, EL and PA speech and their working mechanism are different. In laryngeal speech production, sound waves originated from the vibration of the vocal folds propagate directly from the pharyngeal cavity to the oral cavity. However, in alaryngeal speech production, propagation of the sound wave is more complicated. For example, in PA speech, the source of vibration is a rubber reed located inside the artificial larynx external to the human body. When the sound wave generated from the rubber reed travels through the external mouth tube into the oral cavity, the wave propagated in two directions (Ng & Chu, 2009). One direction is the forward propagation to the mouth and the other one is the backward propagation into the pharyngeal cavity. The wave in backward propagation is then reflected back to the mouth upon the pharyngeal wall. The overlapping pathway of sound propagation might lead to the interference of sound waves, resulting in a resonance pattern more complicated than that of laryngeal speech. The difference in the pathway of sound wave propagation within the vocal tract between the PA and laryngeal speech may have contributed to their difference of formant frequency. Moreover, the possible effect of the sound wave interference in PA speech within the vocal tract on the resultant formant frequency is unknown.

Results of the present study may also imply that, in contrast to laryngeal phonation, the source-filter theory may not be applicable to alaryngeal phonation. For example, in EL speech, the sound is generated by the vibration of the diaphragm of the electrolarynx placed at the neck anterolaterally, near to the floor of the mouth (Ng & Chu, 2009). The muscles at that portion of the neck act as a secondary source for vibration and transmit the wave to the oral cavity. At the same time, it is likely that the sound wave is filtered through the muscles (Ng, Liu, Zhao, & Lam, 2009). As the speech production process by electrolarynx involves the muscles as both the source and the filter, it is questionable whether the independence of the source and filter in the source-filter theory (Fant, 1960; Pickett, 1999) can be applied to EL speech production. Moreover, the process of transmission and filtering of sound waves through the muscles may have caused changes to the formant frequencies.

One of the objectives of this study is to testify whether vocal tract length of alaryngeal speakers is shorter than that of laryngeal speakers. Although the results of this study show that there are no significant different in the vocal tract length between the two groups, the results may be limited by the experimental procedures of the pharyngometer. One of the limitations of the pharyngometer is that it does not allow phonation during the measurement process. It is possible that the vocal tract length may differ during phonation and the results could not reflect the true vocal tract length during vowel production. For example, during TE speech production, the vibratory source, which is the PE segment, is found to be at the level of the 3th to 4th cervical vertebra (C3-C4) by videofluoroscopy (van As, Op de Coul, van den Hoogen, Koopmans-van Beinum, & Hilgers, 2001). However, when the PE segment is at rest, it is lowered to C4-C5. Therefore, the vocal tract length could be regarded as shortened during TE speech production.

The present study provides volumetric information on the vocal tract configuration of alaryngeal and laryngeal speakers by using ART. Yet, data are preliminary and more investigations are suggested to further the understanding of the vocal tract configuration of alaryngeal speakers. A comparative study on the vocal tract configuration within individuals before and after the laryngectomy operation can be carried out to confirm the results of this study. To clarify the relationship between vocal tract length and formant frequency in vowel production, vocal tract dimensions during phonation instead of during solely mouth breathing can be studied using instruments other than pharyngometer to reveal possible difference in vocal tract length between alaryngeal and laryngeal speakers during vowel production. Besides, as this is a pioneering study that applies ART on laryngectomees, it is suggested that reliability and validity of the use of pharyngometry on laryngectomees be evaluated to support the further use of ART on this aspect.

Conclusions

Pharyngometry revealed no significant difference in the vocal tract dimensions, including the length and volume of the oral cavity, pharyngeal cavity and the entire vocal tract, of alaryngeal and laryngeal speakers. The finding suggested that the difference in the formant frequency during vowel production by alaryngeal and laryngeal speakers may be due to factors other than vocal tract configuration, for example, the difference in phonatory mechanism of alaryngeal and laryngeal speakers. The finding also suggested that the independence of the source and the filter in the source-filter theory (Fant, 1960; Pickett, 1999) may not be applicable to alaryngeal speakers. Further investigation of the vocal tract configuration of alaryngeal speakers is suggested to confirm the results of this study. The evaluation of reliability and validity of the use of pharyngometry on laryngeal speakers is recommended.

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