Correlation Between the Position of the Hyoid Bone on Lateral Cephalographs and Formant Frequencies

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Summary: Objectives. The objective of this study is to examine the F1, F2, F3, and F4 during sustained vowels /ɑ/, /i/, /o/, /u/.
Study Design. Prospective cross-sectional study.
Methods. Fifty-two consecutive patients aged between 9 years and 38 years were invited to participate in this study. Linear measurements included linear vertical distance from the hyoid bone to the sella turcica (H-S); linear vertical distance from the hyoid bone to the posterior nasal spine (H-PNS); linear measure from the hyoid bone to the most anterior point of the cervical vertebra C3 (H-C3); and linear vertical distance from the hyoid bone to the mandibular plane (H-MP).
Results. The results showed a moderate and statistically significant correlation between the average fundamental frequency for the vowel /ɑ/ and H-C3, H-S, and H-PNS and another moderate negative correlation between F3 and F4, and the vertical position of the hyoid bone H-C3 and H-S. For the vowel /i/, there was a moderate negative correlation between F1, F3, and F4 and H-S and also a moderate negative correlation between F3 and F4 and H-C3. For the vowel /o/, there was a moderate negative correlation between F4 and H-S and H-PNS. For the vowel /u/, only F4 correlated significantly with H-S.
Conclusion. There is a moderate correlation between the high formants, mostly F4, and the cephalo-caudal position of the hyoid bone.
Key Words: Formants–Hyoid bone–Lateral Cephalograph–Vowel–Pitch.

INTRODUCTION

The vocal tract plays an important role in vocal tract resonance. It starts with the lips and extends to the glottis, spanning the oral, pharyngeal, and laryngeal cavities. Its length and configuration are major determinants of many acoustic properties, among which are formant frequencies. Several studies have used imaging techniques to examine the morphological changes of the vocal tract in relation to voice. Most of these are either reports on the development of the human larynx or reports on vocal tract configuration in relation to speech and different vocal registers.[1–4] Using conventional X-ray or magnetic resonance imaging (MRI), vocal registers were analyzed in relation to the vocal tract dimensions, namely length and form. Marunick and Menaldi investigated the different vocal registers in female singers in relation to the maxillary dental arch. Their results indicated that sopranos, compared with mezzo-sopranos and altos, had shallower palates.[5] Echternach et al have used magnetic resonance images to measure lip opening, jaw position, pharyngeal constriction, and/or laryngeal height among others in relation to male alto and female registers.[6] Sulter et al have used spatial configuration of the vocal tract by MRI using direct and indirect methods to determine vocal tract dimensions.[7] In their study on voice classification and vocal tract dimensions in singers, Roers et al examined X-ray materials of 132 subjects. Different anatomical landmarks were used, such as the upper incisors, atlas, and glottis, and different linear measurements were used to measure the length of the vocal tract, namely the oral, velar, and pharyngeal lines.[8]

In all the aforementioned reports, acoustic properties were analyzed in relation to the length and configuration of the vocal tract with no reference to the hyoid bone position, which is an important anatomical landmark used in vocal pedagogy and in the clinical assessment of patients with voice disorders. Only few studies have radiologically examined the correlation between F0 using the hyoid bone as a radiologic landmark.[9,10] In all these studies, the position of the hyoid bone was investigated in relation to changes in the vocal frequency. In a cross-sectional study of 10 subjects, humming and pitch in relation to the craniofacial/cervical morphology were assessed by Miller et al using MRI.[9] The results indicated the significant effect of note conditions in 27% of the measurements. There was an increase in the craniocervical angles, a rise in the laryngeal and hyoid bone positions in relation to the cranial base, and an increase in the sternum hyoid distance with humming of the high notes. The relationship between laryngeal vertical movement and changes in vocal frequency (F0) has also been investigated by Honda et al.[10] Changes in F0 were coupled with vertical movement of the larynx and lordosis of the cervical spine. Movement of the larynx in the vertical direction results in the rotation of the cricoid cartilage and subsequent tensioning of the vocal folds. MRI results from Honda et al's study indicated that vertical movement of the larynx comprises an effective F0-lowering mechanism.

The purpose of the present study is to provide more insights into the correlation between the position of the hyoid bone and formant frequencies F1, F2, F3, and F4 during sustained vowels

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/ɑ/, /i/, /o/, /u/ using lateral cephalometric measurements in a group of subjects presenting to the orthodontic service.

PATIENTS AND METHODS

Participants

A total of 52 consecutive patients between the ages of 9 years and 38 years presenting for the first time to the division of Orthodontics and Dentofacial Orthopedics at the American University of Beirut Medical Center were invited to participate in this study. Patients with history of orthodontic manipulation, treatment, or orthognathic surgery, as well as patients with congenital facial malformations, namely cleft lip and palate and hemi-facial microsomia, were excluded. Patients with recent history of respiratory tract infection and/or laryngeal manipulation were excluded from the study. Patients with dysphonia as perceived by a senior speech language pathologist at the time of presentation were also excluded from this study. All participants have read and signed the informed consent form approved by the institutional review board.

Materials and procedures

A set of records was taken for every patient, namely lateral cephalographs, using a digital cephalostat (GE, Instrumentarium, Tuusula, Finland) in a standardized fashion and with the head of the patient in natural position. The following landmarks were employed on a lateral cephalometric radiograph: H: most anterior point of the hyoid; S: midpoint of sella tursica; PNS: posterior nasal spine, the spine-like projection from the posterosuperior midline of the horizontal plate of the palatine bone; C3: third cervical vertebra; Go: gonion, a spine-like projection from the posterosuperior midline of the horizontal plate of the palatine bone; Me: menton, the most inferior point on the chin; MP: mandibular plane; V: vertebra. After that, linear measurements were obtained: H-S: linear vertical distance from H to S; H-PNS: linear vertical distance from H to PNS; H-C3: linear measure from H to the most anterior point of C3; H-MP: linear vertical distance from H to MP (Figure 1).

All subjects underwent acoustic analysis using Visi-Pitch IV (Model 3300, KayPENTAX, Montvale, New Jersey), and the average fundamental frequency and habitual frequency were reported. Formant frequencies across F1, F2, F3, and F4 were determined using the Real-Time Spectrogram of VP 3950 (Sona-Speech 2, Model 3650, KayPENTAX). The Sono Match module, using the Real-Time FFT window, was used to confirm the results obtained by the Real-Time Spectrogram. The cursor was placed at the centermost point of the steady-state formant band when looking at the spectrogram. The formants were visually identified, after which the cursor was placed in the middle of the formant's horizontal lines and the value was computed and given.

The mean, standard deviation, and value range were derived for all variables for statistical analyses. Pearson's correlation was calculated to estimate the strength of the relationship between the measurement parameters of the hyoid cartilage and acoustic parameters. We conducted our statistical analyses using *SPSS* Statistics 21 (IBM, Armonk, New York). Statistical significance was set at *P*-values of <0.05 and <0.01.

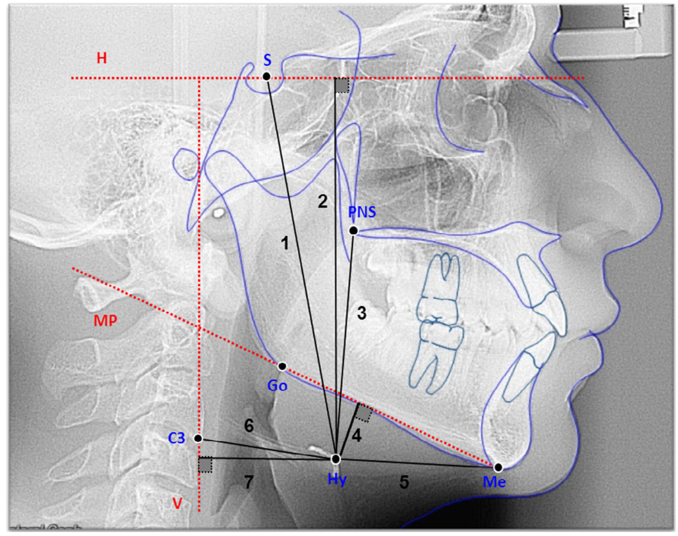

FIGURE 1. The figure shows the landmarks that were employed on a lateral cephalometric radiograph: H: most anterior point of the hyoid; S: midpoint of the sella tursica; posterior nasal spine (PNS): the spine-like projection from the posterosuperior midline of the horizontal plate of the palatine bone;C3: third cervical vertebra; gonion (Go): spine-like projection from the posterosuperior midline of the horizontal plate of the palatine bone; menton (Me): the most inferior point on the chin;MP: mandibular plane; V: vertebra. After that, linear measurements were obtained: H-S: linear vertical distance from H to S; H-PNS: linear vertical distance from H to PNS; H-C3: linear measure from H to the most anterior point of C3; H-MP: linear vertical distance from H to MP.

RESULTS

Demographic data and means of hyoid bone parameters H-C3, H-S, H-PNS, and H-MP

The mean age of the subjects was 17.07 ± 7.20 years with 26.9% being males. The means of the four hyoid bone position parameters are as follows: H-S (mm): 92.81 ± 8.213; H-PNS (mm): 54.62 ± 6.234; H-C3 (mm): 31.6 ± 4.447; and H-MP (mm): 12.52 ± 4.692.

Means of formant frequencies for vowels /ɑ/, /i/, /o/, and /u/

The means of formants F1, F2, F3, and F4 for the vowel /ɑ/ are 836.38 Hz, 1479.42 Hz, 3105.85 Hz, and 3995.27 Hz, respectively. The means of formants F1, F2, F3, and F4 for the remaining vowels /i/, /o/, and /u/ are shown in Table 1.

Correlation between hyoid bone position and formant frequencies F1–F4 for vowels /ɑ/, /i/, /o/, and /u/ in the total group

There was a moderate correlation that was statistically significant between the average fundamental frequency for the vowel /ɑ/ and all the three cephalo-caudal parameters for the hyoid position, namely H-S, H-PNS, and H-C3 (r values of 0.596, 0.445, and 0.481, respectively with *P*-values of 0, 0.001, and 0, respectively as shown in Table 2).

TABLE 1.
Means of Formants F1, F2, F3, and F4 (/ɑ/, /i/, /o/, /u/)

	Mean ± SD			
	Vowel /ɑ/	Vowel /i/	Vowel /o/	Vowel /u/
F1 (Hz)	836.38 ± 114.71	458.88 ± 93.661	547.15 ± 101.335	486.76 ± 130.071
F2 (Hz)	1479.42 ± 132.014	2674.25 ± 359.153	1172.31 ± 211.459	1189.1 ± 548.831
F3 (Hz)	3105.85 ± 275.778	3408.65 ± 303.876	3037.38 ± 300.354	3195.26 ± 469.615
F4 (Hz)	3995.27 ± 244.589	4130.1 ± 206.174	3917.08 ± 245.39	3993.07 ± 238.791

TABLE 2.
Correlation Between Hyoid Parameters and Average F0 and Habitual Frequency

	H-S (mm)		H-PNS (mm)		H-MP (mm)		H-C3 (mm)	
	R	*P*-Value	R	*P*-Value	R	*P*-Value	R	*P*-Value
Average F0 (Hz)	–0.596	<0.0001	–0.445	0.001	–0.134	0.345	–0.481	<0.0001
Habitual frequency (Hz)	–0.619	<0.0001	–0.507	<0.0001	–0.226	0.107	–0.548	<0.0001

There was a moderate negative correlation between F3 and F4 and the vertical position of the hyoid bone as shown with r values for H-C3 and H-S ($r > 0.30$ and P-value < 0.05). There was also a moderate negative correlation between F2 and H-S (r of –0.406 and P-value of 0.003) and between F1 and H-C3 (r of 0.366 and P-value of 0.008). There was a poor correlation between any of the formant frequencies with the position of the hyoid bone in relation to the mandibular plane, referenced by the H-MP variable (all $r < 0.3$ and all P-values > 0.05).

With respect to the vowel /i/, there was a moderate but significant negative correlation between F1, F3, and F4 and H-S (all $r > 0.30$, P-values < 0.05). There was also a moderate negative correlation between F3 and F4 and H-C3 (r values of 0.392 and 0.309 respectively) that was statistically significant (P-values < 0.05). Note that none of the formant frequencies correlated with H-MP (all $r < 0.30$).

With respect to the vowel /o/, there was a moderate negative correlation between F4 and H-S and H-PNS (r values of –0.364 and –.0373 respectively) that was statistically significant (P-values of 0.008 and 0.006 respectively). There was also a moderate negative correlation between F3 and H-C3 (r 0.301) that was statistically significant (P-value 0.03).

For the vowel /u/, there was a moderate negative correlation between F4 and H-S (r of 0.372) that was statistically significant (P-value of 0.014). The rest of the formants did not correlate with any of the remaining cephalometric parameters as shown in Table 3.

Correlation between hyoid bone position and formants F1–F4 for vowels /ɑ/, /i/, /o/, and /u/ in the total group excluding the pubertal subjects

The results in the total group after excluding the pubertal subjects (Females [11–15.5; Males [12–16), referred to as the nonpubertal group, showed similar findings and actually substantiated the results in the overall group, namely the moderate and significant negative correlation between the hyoid bone cephalometric measures and F0 and habitual pitch, and the negative moderate correlation between H-S, H-PNS, and H-MP and the high formants, in particular F4, for all the vowels (Table 4).

DISCUSSION

The length and shape of the vocal tract are responsible for the formants' position and dispersion. From infancy to adulthood, the vocal tract increases more than twofold in length with major anatomical restructuring. At puberty, there is growth of the laryngeal structures and descent of the larynx more in men compared with women. The lowering of the hyoid bone at puberty and its normal position at C3 or between C3 and C4 are partially responsible for the decrease in the formants and their dispersion. As a result, the vocal tract is longer, and the ratios of women's formants to men's formants are 1.18 for F1, 1.17 for F2, and 1.14 for F3.[11]

The position of the hyoid bone in relation to formant frequencies has not been thoroughly investigated in the literature, despite the importance of the hyoid bone position as an anatomical landmark in the clinical assessment of patients with voice disorders, such as muscle tension dysphonia (MTD), There are numerous reports in the literature on the correlation between vocal register transition and vocal tract configuration, with little information on the position of the hyoid bone in relation to formant frequencies using sustained vowels at a modal register. Tom et al have reported on the configuration of the vocal tract during speech in modal register and during singing in falsetto register.[12] For transitions between vocal registers, Luchsinger, using plain X-ray imaging, has reported changes in the laryngeal ventricles in modal vs. falsetto register.[13] Echternach et al using dynamic real-time MRI have also investigated the vocal tract shape during transitions between registers. Their findings indicated only minor changes with a shift from modal to falsetto registers. In a similar study analyzing the differences of the vocal tract shapes in male alto register function, transition in register from modal to stage falsetto was associated with a tilt and a drop in laryngeal height,

TABLE 3.
Correlation Between Hyoid Bone Measurements and the Formants of All Vowels (/ɑ/, /i/, /o/, /u/) in the Total Group of Patients (N = 52)

	H-S (mm)		H-PNS (mm)		H-MP (mm)		H-C3 (mm)	
Formants (Hz)	R	*P*-Value	R	*P*-Value	R	*P*-Value	R	*P*-Value
F1 /ɑ/	−0.11	0.437	−0.178	0.208	−0.06	0.674	−0.366	**0.008**
F2 /ɑ/	−0.406	**0.003**	−0.221	0.115	−0.183	0.194	−0.286	**0.04**
F3 /ɑ/	−0.378	**0.006**	−0.285	**0.04**	−0.045	0.753	−0.454	**0.001**
F4 /ɑ/	−0.484	**<0.0001**	−0.297	**0.033**	−0.214	0.128	−0.357	**0.009**
F1 /i/	−0.383	**0.005**	−0.280	**0.044**	−0.282	**0.042**	−0.143	0.31
F2 /i/	−0.25	0.074	−0.228	0.104	0.039	0.782	−0.147	0.299
F3 /i/	−0.372	**0.007**	−0.244	0.081	0.126	0.372	−0.392	**0.004**
F4 /i/	−0.396	**0.005**	−0.320	**0.026**	−0.027	0.855	−0.309	**0.033**
F1 /o/	−0.068	0.63	−0.071	0.617	−0.011	0.938	0.02	0.891
F2 /o/	−0.054	0.702	0.105	0.46	−0.046	0.745	0.143	0.311
F3 /o/	−0.271	0.052	−0.294	**0.035**	−0.179	0.204	−0.301	**0.03**
F4 /o/	−0.364	**0.008**	−0.373	**0.006**	−0.196	0.164	−0.235	0.094
F1 /u/	0.207	0.145	0.21	0.138	−0.057	0.69	0.249	0.078
F2 /u/	0.178	0.211	0.194	0.172	−0.115	0.423	0.136	0.343
F3 /u/	−0.134	0.353	−0.097	0.501	−0.075	0.605	−0.248	0.083
F4 /u/	−0.372	**0.014**	−0.274	0.075	−0.193	0.216	−0.237	0.126

P-values < 0.05 were put in bold

in addition to pharyngeal narrowing, elevation of the tongue base, and jaw retraction.[14] Along the same line of investigation, Sutter et al used MRI to investigate the relationship between acoustic signals produced in specific vocalized tasks and the spatial configuration of the vocal tract.[7] Three-dimensional measurements of the vocal tract were used to calculate the resonance frequencies, which in turn were compared with actually measured acoustic frequencies. A strong correlation was found between the acoustical signal produced and the spatial configuration of the first two resonance frequencies of vowels /ɑ/ and /i/.

There are few reports on the position of the hyoid bone in subjects with MTD and fewer studies in subjects performing normal phonatory tasks.[9,15] The position of the hyoid bone has been used as an important clinical landmark within the myriad of clinical findings in the assessment of dysphonic patients with muscle tension. In a radiographic study by Lowell et al on 20 subjects, half of whom had MTD vs. a normal control group, the results showed a low to moderate significant correlation between the radiographic position of the hyoid and larynx and the subjective evaluation using palpation. Accordingly, patients

TABLE 4.
Correlation Between Hyoid Bone Measurements and the Formants of All Vowels (/ɑ/, /i/, /o/, /u/) in the Total Group of Patients After Exclusion of the Pubertal Group (N = 24)

	H-S (mm)		H-PNS (mm)		H-MP (mm)		H-C3 (mm)	
Formants (Hz)	R	*P*-Value	R	*P*-Value	R	*P*-Value	R	*P*-Value
F1 /ɑ/	−0.44	**0.031**	−0.412	**0.045**	−0.343	0.101	−0.477	**0.018**
F2 /ɑ/	−0.518	**0.01**	−0.479	**0.018**	−0.301	0.153	−0.293	0.165
F3 /ɑ/	−0.475	**0.019**	−0.394	0.057	−0.085	0.692	−0.493	**0.014**
F4 /ɑ/	−0.656	**0.001**	−0.631	**0.001**	−0.421	**0.041**	−0.499	**0.013**
F1 /i/	−0.554	**0.005**	−0.658	**<0.0001**	−0.327	0.119	−0.355	0.089
F2 /i/	−0.384	**0.064**	−0.292	0.166	−0.131	0.542	−0.449	**0.028**
F3 /i/	−0.503	**0.012**	−0.419	**0.042**	−0.102	0.637	−0.509	**0.011**
F4 /i/	−0.678	**0.001**	−0.611	**0.002**	−0.226	0.311	−0.636	**0.001**
F1 /o/	−0.200	0.349	−0.234	0.271	−0.159	0.458	−0.102	0.636
F2 /o/	−0.430	**0.036**	0.454	**0.026**	−0.253	0.233	−0.044	0.839
F3 /o/	−0.465	**0.022**	−0.371	0.074	−0.099	0.645	−0.588	**0.002**
F4 /o/	−0.641	**0.001**	−0.586	**0.003**	−0.333	0.112	−0.402	**0.051**
F1 /u/	0.222	0.309	0.165	0.451	−0.006	0.980	0.149	0.498
F2 /u/	0.105	0.632	0.063	0.774	−0.186	0.396	−0.03	0.893
F3 /u/	−0.240	0.270	−0.187	0.392	−0.207	0.344	−0.396	0.061
F4 /u/	−0.442	**0.066**	−0.383	0.117	−0.180	0.457	−0.284	0.253

P-values < 0.05 were put in bold

with MTD had higher positioned hyoid bones compared with subjects with no voice disorders.[16] Similarly, a study by Izadi and Salehi on the correlation between the hyoid bone position and pull and the perceptual vocal characteristics has indicated the presence of congruence between voice quality and hyoid bone position and pull. The authors have used numerous assessment measures that included palpation, laryngeal videostroboscopic examination, and acoustic analysis. In summary, subjects with a pulled-up hyoid bone had a rough voice whereas those with a pulled-down hyoid bone had a straining voice.[15] With respect to normal phonatory tasks, studies have also demonstrated changes in the cranio-cervical angles and cephalo-caudal positions of the hyoid bone with changes in the fundamental frequencies, namely elevation of the hyoid bone with an increase in vocal pitch.

In all the aforementioned reports, there is consensus that the position of the hyoid bone at rest and during phonation can be used as a clinical indicator of voice quality in patients with MTD or during changes in vocal pitch. No prior study has examined the cephalo-caudal position of the hyoid bone with respect to the skull base in relation to the fundamental frequency and formant characteristics in nondysphonic subjects. Our study does not examine the position of the hyoid bone in relation to transitions in vocal registers or changes in the fundamental frequency. The focus of this investigation is to assess the correlation between the formant frequencies and the position of the hyoid bone at a comfortable pitch and loudness. The results of our study indicate that in all vowels, /ɑ/, /i/, /o/, and /u/, formant F4 moderately and significantly correlated with at least one vertical parameter, H-S, and in vowels /ɑ/ and /i/ there was a moderate and significant correlation between F3 and F4 and H-S and H-C3. The clinical significance of this study lies in the presence of a negative correlation between the position of the hyoid bone and the fundamental frequency and in particular, the high formants. This means that subjects with a low F0 and a rather deep voice tend to have higher H-C3, H-S, and H-PNS, indicating a lower position of the hyoid bone. That being said, the radiologic position of the hyoid bone can be used as an anatomical clinical landmark in the evaluation of voice quality and classification of nondysphonic subjects.

Given that the position of the hyoid bone in relation to the cranial base and cervical vertebra is an indicator of the length of the vocal tract, the findings of this study are aligned with numerous reports in the literature indicating that the vocal tract length correlates with the position of the formant frequencies, more so for the higher formants, namely F3 and F4. The acoustic properties of the vocal tract have been investigated with respect to both sung and spoken voices, with different areas shown to be responsible for the location and dispersion of formant frequencies. Fant and Bavegard have demonstrated that shortening of the vocal tract by 0.5 cm increases F5 and F4 to a lesser extent.[17] Sundberg has investigated the acoustical and physiological mechanisms of formant generation with respect to the vocal tract shape, length, and position. He has shown that the position and dispersion of formants F1–F5 are sensitive to the area functions of the vocal tract, in particular F4 and F5.[18,19] In 1960, Fant also showed that the laryngeal cavity has a marked influence on the F4 of /ɑ/, /u/, and /i/.[20] Using vocal tract area functions, Takemoto et al have shown that expansion or constriction of the laryngeal ventricles and vestibules results in fluctuation in F4 frequency.[21] The same authors have also demonstrated that the laryngeal cavity generates primarily the fourth formant with a little contribution to the other formants. This role has been attributed to the open-tube resonance of the vocal tract proper.[22] The piriform sinuses on the other hand act as side branches to the vocal tract generating a spectrum in the frequency range of 4–5 KHz.[23]

The main limitation of the present study is the lack of measurements of the vocal tract length. It is true that the hyoid bone is an anatomical marker of the vocal tract, but the position of the hyoid bone remains an indirect estimate of the length of the vocal tract. This study simply demonstrates that the high formants significantly correlate with the position of the hyoid bone but cannot conclude that they correlate with the length of the vocal tract. Nevertheless, the results of this investigation cast important information on the significant correlation between the position of the hyoid bone and the high formants, namely F3 and F4, for most of the vowels at a comfortable pitch and loudness.

CONCLUSION

There is a moderate correlation between the high formants, mostly F4, and the cephalo-caudal position of the hyoid bone in relation to the base of the skull and the third cervical vertebra C3.

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