# On the Acoustic and Articulatory Characterization of the Effects of Arabic Pharyngealized Consonant on Adjacent Vowel

X-ray Study of Arabic Pharyngealized Consonant

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***Abstract*—The phonetic and phonological properties of the pharyngealized consonants are essential for understanding how they affect the phonological systems of the languages in which they occur. This study focuses on consonants with a primary or secondary pharyngeal articulation, which occur in Moroccan Arabic dialect. Pharyngeal or pharyngealized consonants are rare and they are understudied. The manifestation of pharyngealization is centered between the consonant and vowel as in distortion of the formant transitions in the adjacent vowel. This study used ariculatory and acoustic data to characterize the pharyngealized Moroccan Arabic dialect sound and highlight their effect on neighboring vowel. The acoustic results from very specific articulatory configuration show that the vowel formants are influenced by the pharyngealized contexts and the articulatoy gestures spread on the adjacent vowel. It was also found that the pharyngealized and the voiced pharyngeal consonants have similar effects on the neighboring vowel.**

***Keywords-pharyngealized consonants; Arabic vowels; coarticulation; x-ray images; vocal tract.***

## I. INTRODUCTION

During speech production, a series of articulatory gestures are realized by means of the phonatory organs movement in the vocal tract. The passage from the production of isolate phonemes to continuous speech involved an enormous articulatory and acoustic variability. Today, technological developments in medical imaging, progress in the observation of organs and muscles facilitated by new tools, have produced significant advances in the understanding of the mechanisms involved in speech production [1].

In this work, we indicate the methods and techniques used to observe the activity of organs in speech production and the possibilities offered by the vocal tract. The way of envisaging how this is done is to situate the process in a physiological theory of speech production and invoke an articulatory model. Close attention to the movement of the phonatory articulators involved in speech production can shed light on the consequences of certain actions on other organs. The great mobility of the phonatory organs offers a rapid modification of the vocal tract, leading to the modification of the size of the oral cavity and the pharyngeal cavity.

The pharynx is a passageway linking the oral cavity with the esophagus and the nasal cavity with the larynx. It runs vertically from the base of the skull to the level of the sixth cervical vertebra [2]. It serves as the first resonator for laryngeal sound. Regarding the role of the pharynx in speech production, it is important to note that the alterations in the size and shape of the pharyngeal cavity play an important role in determining voice quality, this is why the researchers paid particular attention to the anatomical and muscular description of the pharynx. Thus the raising or lowering of the larynx alters the length of the pharyngeal cavity which leads to acoustic consequences due to the change in the vertical dimension of the pharynx; larynx lowering results in the lowering of formant values [3].

In this study, we deal with the Arabic sound which occurs in the pharyngeal zone of the vocal tract, the pharyngealized consonant /$t^{ʕ}$/ which shows the highest degree of emphaticness [2]. Laufert and Baer cited Panconcelli-Calzia (1924. pp. 48-49) who suggested processes for the emphatic consonants: contraction of the muscles of the hyoid bone, raising of the larynx, constriction of the pharynx due to the actions of the constrictor muscles [2]. According to Catford's definition, when there are two simultaneous articulations, an articulation in the pharynx is considered the secondary one [4] (the Pharyngeal constriction generally constitutes a secondary articulation). In Arabic and other Semitic languages, pharyngealization involves a secondary articulation, it is defined as an articulation performed separately in addition to the primary articulation associated with a sound. The secondary articulation according to definition is less constricted than the primary articulation. The studies of emphatics based on experimental data, mainly from x-ray as in Ghazeli’s study, he conclude that the pharyngeal sounds are articulated in the lower part of the pharynx, the uvular sounds have a constriction in the upper oropharynx and the emphatics have a secondary tongue retraction midway in the pharynx between the place of articulation of uvular and pharyngeal [5].

Giannini and Pettorino [6] examined one Arabic speaker of a Baghdadi dialect and presented acoustic and radiographic data. Their acoustic results are that for the emphatics the first and second formant Fl and F2 approach each other: Fl rises and F2 lowers. The third formant F3 is almost unchanged. They interpreted their radiographic results as showing a constriction in the pharynx for the emphatic sounds.

In summary, our main aim in this paper is to study the production of the Moroccan Arabic pharyngealized sound /tˤ/, its effects on adjacent vowel /a/ and we compare them with the pharyngeal consonants /ʕ/. Using cineradiography films of the vocal tract, we examined the hypothesis that both the pharyngeal and pharyngealized consonants are consistently produced with a pharyngeal constriction, and with a raising larynx and that pharyngeal constriction and larynx height are thus an articulatory features associated with these sounds, we refer to the acoustic and radiographic data to examine this issue. We also explore the association of the two consonants effect on the adjacent vowel /a/ as in /ʕṱa/. The methods and tools used for data processing and for measuring organ displacements are given in Section 2, the obtained results are given in Section 3 and the conclusion is given in Section 4.

## II. METHODS AND TOOLS

This study based on experimental data, mainly from x-ray images of the vocal tract and acoustic data, these articulatory and acoustic data were taken from a database (DOnnées Cinéradiographiques VAlorisées et recherches sur la Coarticulation, Inversion et évaluation de Modéles physiques) (DOCVACIM) [7]. We have drawn the main articulator contours, particularly those of the tongue, lower and upper lips, the larynx, the glottis, the jaw, the hard palate and the hyoid bone.

### A. Delineating Articulator Contours

We used software, called "X-articulators" [8], enabling several tracking tools to be used according to the nature of articulators. The "X-articulators" software has been designed to exploit automatic or semi-automatic tracking tools, it provide several tools to the exploitation of contours easier [8], and to construct articulatory models from the articulator contours via Principal Component Analysis (PCA). The main articulator are approximated by the following parameters: The lip deformations are approximated by two factors (roughly aperture and protrusion), and the lower part of the pharynx (including the larynx and the epiglottis) is represented by two factors (larynx height, glottis), the tongue by three factors (apex, tongue dorsum, tongue body) [9]. It provides also several tools to make the exploitation of contours easier, since it is important to relate contours to phonemes uttered, it is possible to import a file of phonetic annotations. Thus, before the delineation of the phonatory organs contours a phonetic annotations and Synchronization of the annotation is carried out.

The radiographic film used in this study, consists of vocal tract x-ray images of a native Moroccan Arabic adult male speaker, and the acoustic data consists of sentences in Moroccan Arabic dialect. For this study, we processed the images that correspond to the production of Arabic vowel /a/ adjacent to pharyngealized consonant /tˤ/. These articulatory data allowed us to extract combinations of articulators for this phonetic type.

### B. Treatment of Acoustic Data

The acoustic database consists of sentences uttering by an adult male speaker in Moroccan Arabic dialect, which is the L1 of the speaker. In this study we selected sequences that contain vowel /a/ in pharyngealized environment. We used the software Praat to segment the sentences into phonemes and also for the phonetic annotation, the length of each sentence is measured and also the duration of the entire sequence. After segmentation, we synchronized each phone with the corresponding x-ray images of the speaker vocal tract. Thus, for each phoneme we have the corresponding vocal tract x- ray images, and then we processed the vocal tract x-ray images corresponding to each phoneme.

The contours are annotated and exploited for direct measurement of the articulators' displacement.

### C. Measurment of the phonatory organs displacements

The method of measurement of the displacement of the phonatory organs is based on an angular reference. Knowing that the vocal tract configurations are different for each speaker that is the reason why we make an adapted grid for our subject. An orthonormal basis is drawn beforehand on tracing paper and used with the adapted grid to measure the articulators' displacements [10]. This method allows the observation of the displacements of the phonatory organs, therefore it is used in the analysis of numerous data collected on different subjects. a reference image which corresponds to a rest position is chosen to reproduce on the millimeter layer, where the orthonormal reference has been drawn before, the fixed elements of the vocal tract, particularly the upper incisor and the hard palate, thus, making the upper incisor particularly reliable as a reference point. The traced part will then be superimposed on each sketch as finely as possible. All the positions of the phonatory organs are therefore calculated relative to the upper incisor. In our study, we focused on the measurements of the larynx center position, the constriction opening, the constriction location and the hyoid bone position, knowing that these components are the effective gestures for producing the pharyngeal and pharyngealized consonants.

## III. RESULTS

Tables 1 summarizes the position of the hyoid bone and the larynx center, the constriction opening and location, during the production of the pharyngeal /ʕ/, the pharyngealized consonants /tˤ/ and during the production of the short vowel /a/ adjacent to these consonants.

We focused on the vertical movement of the larynx and the hyoid bone given by the vertical coordinate (y) relative to the rest position, all measures are carried out relative to the reference point (upper incisor). The Average Values (AV) with Standard Deviation (SD) are calculated, the values are given in centimeters. We calculate the elevation of the larynx center and the hyoid bone relative to the rest position.

TABLE I. MEASURES REGARDING THE HYOID BONE POSITION, THE LARYNX CENTER POSITION, THE CONSTRUCTION OPENING AND CONSTRUCTION LOCATION: IN THE REST POSITION, DURING THE PRODUCTION OF THE PHARYNGEAL /ʕ/ , DURING THE PHARYNGEALIZED CONSONANT /Tˤ / AND FOR THE ADJACENT VOWEL /A/.

| | Hyoid Bone (HB) position (y) cm | Larynx Center (LC) position (y) cm | Construction opening (cm) | Construction location (cm) |
|---|---|---|---|---|
| Rest position | 4.2266 | 6.1732 | - | - |
| /ʕ/ in /ʕtˤah/ | 2.8111 | 4.6995 | 0.9872 | 14.6384 |
| /tˤ/in /ʕtˤah/ | 3.0527 | 4.6535 | 0.0583 | 1.4485 |
| /tˤ/in /tsutˤina/ | 3.3362 | 5.5298 | 0.0878 | 1.7827 |
| /tˤ/in/tˤwaʒen/ | 3.3649 | 5.9345 | 0.0877 | 1.9483 |
| AV of /tˤ/ in plain cotexts | 3.3505 SD(0.17) | 5.7321 SD(0.654) | 0.0877 | 1.8655 |
| /a/ in /ʕtˤah/ | 3.2391 | 5.1861 | 0.5847 | 1.1145 |
| $/a_1/$in $/ma_1t^ʕa_2ruʃ/$ | 4.1298 | 5.9788 | 1.1006 | 12.9673 |
| $/a_2/$ in $/ma_1t^ʕa_2ruʃ/$ | 3.4968 | 5.8149 | 0.5756 | 1.4485 |
| $/a_1/$ in $/ba_1t^ʕa_2t^ʕa_3/$ | 3.7440 | 5.8270 | 0.9887 | 13.3014 |
| $/a_2/$ in $/ba_1t^ʕa_2t^ʕa_3/$ | 3.4715 | 5.61 | 1.0605 | 0.8338 |
| $/a_3/$ in $/ba_1t^ʕa_2t^ʕa_3/$ | 3.7609 | 5.6995 | 0.9559 | 13.1343 |
| Average values for /a/ in /tˤ/ contexts | 3.6123 SD(0.2909) | 5.6717 SD(0.2538) | 0.8163 SD (0.2697) | 1.1322 |
| /a/ in plain contexts | 3.9359 SD(0.336) | 5.8118 SD(0.271) | 1.2164 | 0.9474 |

For the pharyngealized /tˤ /, the larynx center position is at about 5.732cm, with SD =0.654, the larynx center rises by 0.8 cm relative to the rest position. The hyoid bone is at 3.35cm, and SD=0.17, the hyoid bone rises by 0.87 cm. The constriction location is at 1.87cm and the constriction opening is about 0.09cm.

In the context of the word /ʕtˤah/, the larynx center position is 4.65cm, it rises about 1.52 cm. The hyoid bone is at 3.05cm, it raises by 1.17 cm relative to the rest position. The constriction location is at 1.45cm and the constriction opening is 0.06cm.

During the production of the pharyngeal consonant /ʕ/, the larynx center rise by about 0.87 cm relative to the rest position and the hyoid bone raise by 0.72 cm. The constriction location is at 13.76cm and the constriction opening is 1.16cm.

What is noticed in our study is the remarkable influence of the pharyngealized consonant /tˤ/ on the articulation of /ʕ/ in the word /ʕtˤah/. If we compare the larynx center and the hyoid bone position during the production of /ʕ/ in the word /ʕtˤah/ and during the production of /ʕ/ in the word /ʕlaʃ/ [11], we noticed that the larynx center moved up to 4.699 cm, so it rises by 1.47 cm relative to the rest position, 0.674 cm more than in the case of /ʕlaʃ/ and 0.601 cm more than the average value of the larynx center position during the production of /ʕ/ in the plain coronal contexts. The hyoid bone reaches the value 2.81 cm, it rises by 1.41 cm relative to the rest position; 1.40 cm more compared to the production of /ʕ/ in the word /ʕlaʃ/ and 0.94 cm more than the average value of the hyoid bone position in the different studied contexts of /ʕ/ [11]. Likewise, the pharyngealized /tˤ/ is influenced by /ʕ/, where the larynx center rises by about 1cm more than in the plain coronal contexts. So, there is a mutual effect of the two consonants. Regarding the constriction location and opening, the software x-articulator gives us these two parameters as follow: The constriction is given by the point of the tongue whose distance to the palate (measured by orthogonal projection) is minimal. This distance gives the opening of the constriction. To locate the position of the constriction, the outline of the palate is used and the length of the path between the upper incisor and the place of the constriction is calculated. When there is a contact between the tongue and the palate, it is the point of the most onward constriction in the vocal tract that is chosen [8][9]. We can conclude from the obtained results that the primary articulation for /tˤ/ is located at 1.45 to 1.87 cm relative to the upper incisor and the constriction opening is about 0.06 to 0.09 cm. the secondary constriction is located at 12.96 to 13.3 cm and the constriction opening is 0.98 to 1.1 cm. we noticed that the primary constriction is more constricted than the secondary one and the location of the secondary constriction for the pharyngealized /tˤ/ is close to that of the pharyngeal /ʕ, ħ/ which are at about 13.76 to 14.63 cm. the difference is 0.8 cm to 2.16 cm.

In the second part of this section, we explore the articulatory effects of these consonants on the adjacent vowel /a/. The larynx center position and the hyoid bone positions are measured during the production of the vowel /a/ in plain coronal contexts, the average value of the larynx center position is 5.81 cm, and the value of SD is 0.27, the larynx center rises by 0.36 cm and the hyoid bone is at 3.935 cm, and SD =0.3, the hyoid bone rises by 0.29 cm. In the pharyngealized environment /tˤ/, the larynx center rises by 0.50 cm relative to the rest position, it rises 0.14 cm more compared to that measured in plain coronal context. The hyoid bone rises by 0.61 cm (0.32 cm more).

As mentioned earlier, the acoustic output varies according to the behavior of the active gestures and the obtained results from the articulatory study lead to additional questions about the acoustic consequences of change in the vertical position of the larynx on vowel adjacent to the pharyngealized /tˤ/. An acoustic study of the vowel quality was conducted in order to determine the extent to which vowels could be affected by that environment. The software Praat is used for the segmentation of the words into phonemes and for the measurement of the formants values. The table II summarizes the formants values of the vowel /a/ in pharyngealized neighboring, in plain coronal contexts and in the voiced pharyngeal neighboring.

The formants are explored for our subject: For the vowel /a/ in plain coronal environment, the average value of F1 is 519.60 Hz with standard deviation SD equal to 46.46, the value of F2 is 1573.437 Hz, and SD =94.37, F3 is equal to 2485.809 Hz, with SD =137.43, the value of F4 is 3676.291, and SD =95.33.

In /tˤ/ neighboring, F1 increases by 138.52 Hz, F2 decreases by -314.15 Hz, F3 and F4 undergo a moderate increase of 52.33 Hz and 23.88 Hz respectively. In the case of /ʕtˤa/, F1 increases by 198.98 Hz, F2 decreases by -232.48 Hz, F3 remain stable, and F4 increases by 123.72 Hz.

In this study, we compare the effects of the pharyngealized consonant / tˤ/ on adjacent vowel /a/with that of the pharyngeal /ʕ/. The effects of the pharyngealized /tˤ / and the pharyngeal /ʕ/on the formants values of /a / are: F1 increases by about 134.79Hz in /ʕ/ environment, and by 138.52 Hz in /tˤ/ environment, the effect of the pharyngeal /ʕ/ is similar to that of the pharyngealized/tˤ/and in the context of /ʕtˤah/, F1 increases by about 198.98 Hz. F2 in the environment of /ʕ/ increases by about 132.78 Hz, in the environment of /tˤ /, it decreases by about -314.15 Hz. In the word /ʕtˤah/, it decreases by -232.48 Hz. This result agrees with the founding of Al-Ani [12], he found a considerable drop of F2 in vowels following pharyngealized consonants compared to plain consonants. Ghazeli also reported that all vowels have a lower F2 after pharyngealized consonants [5]. We noticed that /ʕ/ decreases the effect of /tˤ/ by about 81.67 Hz. F3 is less influenced by both /tˤ/ and / ʕ/, so in the context of the word /ʕtˤah/, it remains stable. F4 increases by 91.89 Hz in the environment of/ʕ/, by 23.88 Hz in the environment of /tˤ/, and it increases by 123.72 Hz in the word/ʕtˤah/. F4 is less influenced by /tˤ/ and a little more by /ʕ/, so in /ʕtˤah/, the effects of /ʕ/ and /tˤ/ are superimposed.

Comparing the articulatory and the acoustic results, we noticed a correlation between the degrees of the articulatory gestures spreading on the adjacent vowel /a/with the acoustic consequences. Thus, in the word /ʕtˤah/, the pharyngeal /ʕ/ adjacent to the pharyngealized /tˤ/ and both adjacent to the vowel /a/, the larynx center rises during the production of /a/ at 0.987 cm, it is increased by 45.08% relative to the context /ʕa/ (0.542 cm) and by 40.52% relative to the context /tˤa/ (0.587 cm) [11].

TABLE II. FORMANTS VALUES OF THE SHORT VOWEL/A/ IN DIFFERENT CONTEXTS: (/ʕ / AND /Tˤ/) NEIGHBORING AND IN PLAIN CONTEXTS

| Formants / /a/ in /ʕ/and /tˤ/ neighboring | F1(Hz) | F2 (Hz) | F3 (Hz) | F4 (Hz) |
|---|---|---|---|---|
| /a/ in /ʕtˤah/ | 718.58 | 1340.96 | 2487.67 | 3800.35 |
| /a$_1$/ in/ma$_1$tˤa$_2$ruʃ/ | 659.81 | 1278.10 | 2601.01 | 3643.81 |
| /a$_1$/in/ba$_1$tˤa$_2$ tˤa$_3$ / | 674.1 | 1275.05 | 2471.15 | 3658.03 |
| /a$_2$/in /ma$_1$tˤa$_2$ruʃ/ | 649.26 | 1256.64 | 2489.54 | 3674.53 |
| /a$_2$/in/ba$_1$tˤa$_2$ tˤa$_3$ / | 652.2 | 1359.74 | 2548.24 | 3805.53 |
| /a$_3$/in/ba$_1$tˤa$_2$ tˤa$_3$ / | 655.24 | 1126.95 | 2580.75 | 3718.96 |
| Average value of /a/ formants in /tˤ/ neighboring | 658.12 | 1259.29 | 2538.13 | 3700.17 |
| /a/ in /ʕ/ neighbouring | 654.39 | 1706.22 | 1051.83 | 2539.67 |
| /a/ in plain neighboring | 440.50 | 1418.58 | 2566.69 | 3794.06 |
| /a/ in / tˤ/ (%) | 39.49% | -11.22% | -1.1% | -2.47% |
| /a/ in /ʕ/ (%) | 48.55% | 20.27% | -59% | -33% |
| /a/ in /ʕtˤah/ (%) | 63.13 % | -7.47% | -3.07% | 0.16% |

The value of F1 increased by about 63.13%, in the context of the word /ʕtˤah/ compared to plain coronal context. And it is increased by about 23.64% compared to/tˤ/ neighboring and by 14.64% compared to /ʕ/ neighboring. The second formant F2 drops considerably in /tˤ/ neighboring by about 11.22%, the effect of /tˤ/ on F2 is decreased in the word /ʕtˤah/ (7.47%), the consonant / ʕ/ halves the effect of /tˤ/. F3 is less influenced by /tˤ/ also in the word /ʕtˤah/, the variation does not exceed 3%. Likewise for the fourth formant F4 the variation is at about 0.16%.

## IV. CONCLUSION

In this study, the articulatory and acoustic aspects of the production of the pharyngealized consonant /tˤ/are explored. We compared these aspects with those of the pharyngeal consonant /ʕ/. The effects of the association of the pharyngeal consonant with the pharyngealized one as in the word /ʕtˤah/ on the adjacent vowel /a/are investigated.

We noticed that the raising of the larynx center and the hyoid bone is in the same range during the production of both /ʕ/ and /tˤ/ (about 0.8 cm), and F1 increases by 48.5% in /ʕ/ neighboring and by about 39.49% in /tˤ/ neighboring. The production of the two consonants successively /ʕtˤ/ in the word /ʕtˤah/ the larynx center and the hyoid bone rise doubly by about 1.5 cm. So, we observe that the gesture is superimposed and the acoustic effect on F1 also is raised, we noticed a correlation between the articulatory effect and the value of the first formant F1.

In summary, /ʕ/ and /tˤ/have a similar effect on F1 in CV context and in CCV context F1 undergoes a moderate increase compared to CV context about 14% to 23%. F2 increases by 132.78 Hz in /ʕ/ neighboring and drops by -314.15 Hz in /tˤ/ neighboring, in /ʕtˤah/ it drops by -232.48 Hz, so the association of the two types of consonants reduced their effects on F2 and the effect of /tˤ/ is dominant. /ʕ/ decreases the effect of /tˤ/ on F2 by about 81.67 Hz in the word /ʕtˤ ah/.

F3 is less influenced by both /tˤ/ and /ʕ/, F4 is not influenced by the pharyngealized /tˤ/.

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