Effects of maxillary protraction with an orthopedic facemask on fricatives

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Introduction: This prospective cohort study aimed to investigate the effect of rapid maxillary expansion (RME) and orthopedic facemask (FM) treatment on the acoustic properties of fricative sounds (/s/ and /ʃ/) through objective and subjective (perceptual) assessments. **Methods:** Twenty-two patients (7 females and 15 males; mean age: 11.27 ± 1.38 years) underwent speech recordings at 4 time points: immediately before RME (T0), 2 weeks later (immediately before FM application, T1), 3 months later (T2), and 1 week after treatment (T3). Speech therapists recorded the data and conducted acoustic analyses using Praat software. Acoustic parameters—duration, spectral peak, center of gravity, and second formant transition—were analyzed for /s/ and /ʃ/ in monosyllabic words with /a/, /u/, and /ı/ vowels in both word-initial and word-final positions. Data were statistically analyzed using repeated measures analysis of variance and the Friedman test. Cephalometric radiographs were taken at T0 and T3. **Results:** After RME and FM therapy, duration decreased significantly in the word-initial positions of /s/ and /ʃ/ ($P = 0.002$). Spectral peaks decreased significantly in the word-initial and word-final positions during treatment for both /s/ ($P < 0.001$) and /ʃ/ ($P = 0.007$), returning to baseline by T3. However, a significant overall decrease persisted ($P < 0.001$). Center of gravity also decreased significantly during treatment ($P < 0.05$), whereas second formant transition values did not change. A perceptual evaluation revealed high articulation accuracy (2.00) at T0 for all evaluations, a significant decrease at T2 with increased scores (3.65 for /s/ and /ʃ/ total, 4.00 for overall intelligibility, $P < 0.001$), and a subsequent improvement at T3 (1.33 for all evaluations, $P < 0.001$), with scores significantly lower than at T0 ($P < 0.001$). **Conclusions:** RME and FM therapy led to favorable structural and phonetic changes. Improvements in acoustic properties and perceptual scores suggest effective adaptation and enhanced articulation after treatment. (Am J Orthod Dentofacial Orthop 2025;■:■-■)

Articulation disorder is characterized by the inability to produce perceptually acceptable versions of certain sounds, either in phonetic contexts or in isolation. It is particularly common in those with Class III malocclusions.[1] It impairs social communication and affects educational development, career opportunities, and quality of life. It may also lead to negative perceptions, with people being misjudged as having low intelligence or being disabled.[2] Speech problems are the most common type of communication disorder, occurring in 41.8% of children aged 3-10 years and 24.4% of adolescents aged 11-17 years.[3] The prevalence of perceptual speech distortions is reported to be 16-25 times higher among patients with dentofacial disharmony than in the general population.[4,5]

Dental malocclusions and posterior crossbites have been associated with specific phonetic changes.[6] Class III malocclusions are among the most challenging orthodontic problems to manage. Their etiology involves both genetic and environmental factors, which are believed to stimulate condylar growth and result in mandibular prognathism.[7] The prevalence of Class III malocclusions varies from 0.5% to 10% across populations, with skeletal discrepancies identified in three-quarters of affected patients.[7] Rapid maxillary expansion (RME) combined with an orthopedic facemask (FM) is the most widely used treatment protocol for growing patients. It can alter the skeletal position and tongue-teeth-lip relationship,[8] such as improving jaw

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relationships, increasing tongue space, and optimizing lip-tooth positioning.[9] On the basis of a long-term follow-up study[10] and cone-beam computed tomography,[11] it is more effective when started during the early mixed-dentition phase (6 years 9 months). However, studies comparing the effects of FM treatment at different stages, with mean ages of 9 years 8 months vs 12 years 6 months[12] and 7-8 years vs 12-13 years,[13] observed no significant differences in treatment outcomes, indicating that it constitutes a feasible and effective therapeutic approach for older children.

Speech is a highly complex process involving various body parts, including the brain, diaphragm, lungs, larynx, vocal cords, nose, maxilla, teeth, tongue, and lips.[14] Consequently, morphologic changes in these structures can affect speech. Although studies have demonstrated speech problems in patients with Class III malocclusions[4] and evaluated the effects of orthognathic surgery on speech,[1,15–17] no studies have specifically examined speech changes after RME and FM therapy for Class III malocclusions.

Therefore, this study aimed to investigate the effects of RME and FM therapy on the speech process. Its primary aim was to evaluate the impact of RME and FM therapy on speech production, with a particular focus on phonetic changes and improvements in articulation in patients with Class III malocclusions. Its secondary aim was to assess the perceptual analyses of speech and evaluate the relationship between the skeletal and dental changes induced by RME and FM therapy and the improvement in speech function. The null hypothesis was that dental and skeletal changes induced by RME and FM therapy would not affect pronunciation, indicating no significant difference in speech production before and after the RME and FM therapy.

MATERIAL AND METHODS

Subjects

This prospective cohort study received ethical approval from the Clinical Research Ethics Committee of Erciyes University (approval date: January 20, 2021; approval number: 2021/64). Informed consent was obtained from all patients and their parents. The patients included in this study were recruited between June 2021 and January 2023 at the Department of Orthodontics, Faculty of Dentistry, Erciyes University. A power analysis was conducted using the Wilcoxon signed rank test (matched pairs) for a 2-way alternative hypothesis using G*Power software (version 3.1.9.6; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). The effect size was estimated based on Macari et al,[18] who examined the effect of RME on speech characteristics, reporting pretreatment (1461.9 ± 143.8) and posttreatment (1332.5 ± 173.5) values for the second formant (F2) frequency for the vowel /ɑ/. Considering a significance (α) of 0.05, power ($1 - \beta$) of 0.90, and effect size (d) of 0.805, the required sample size was estimated as 20. Therefore, this study included 22 patients scheduled for treatment with RME and FM therapy in the Department of Orthodontics. The cohort consisted of 7 female and 15 male patients, with a mean age of 11.27 ± 1.38 years.

All patients met the following inclusion criteria: (1) skeletal Class III relationship and ANB $<0°$; (2) presence of an anterior crossbite (<0 mm); (3) indication for RME and FM therapy; (4) normal or decreased vertical dimension (SN/GoGn $<38°$); (5) normal or increased overbite (>2 mm); (6) normal maxillary palate, rugae, and incisor morphology; (7) typical receptive and expressive language skills; and (8) native Turkish speaker and monolingual.

All patients did not meet the following exclusion criteria: (1) intellectual disability preventing the ability to follow commands; (2) congenital or acquired craniofacial deformities (eg, cleft lip and palate); (3) syndromes affecting the musculoskeletal system and/or speech; (4) history of sequelae or psychological trauma that could impact speech; (5) presence of coexisting speech and language disorders (eg, stuttering or motor speech disorders); (6) noncompliance with treatment (the absence of expected marks on the forehead and chin from regular FM use, no change in overjet during the first 3-4 months of treatment, or based on observations by parents) or improper FM use; and (7) previous speech therapy, phonetic medical history, hearing impairments, or perceptual issues that could interfere with pronunciation analysis.

RME and FM procedures

A tooth and tissue-supported splint-type RME appliance with full coverage was used in all subjects. It was cemented with glass ionomer and incorporated the same expansion screw (Forestadent, Pforzheim, Germany; one-quarter turn = 0.22 mm). Maxillary expansion followed a rapid protocol, consisting of 2 one-quarter turns per day for the first 10-14 days, followed by one-quarter turn per day until the maxillary molars' lingual cusps aligned with the mandibular molars' buccal cusps. The opening of the midpalatal suture was confirmed using occlusal radiographs on days 10-14.

The subjects in both groups used a Petit-type FM (American Orthodontics, Armonk, NY). Elastic bands (American Orthodontics) were adjusted to exert 350-

Table I. Lateral cephalometric changes after RME and FM therapy

Variables	*T0*	*T3*	*Difference*	P *values*
SNA	81.72 ± 3.33	84.52 ± 3.64	2.80 ± 1.73	<0.001†
SNB	84.50 ± 3.83	82.87 ± 4.35	−1.63 ± 1.54	<0.001†
ANB	−2.77 ± 2.26	1.65 ± 3.42	4.41 ± 2.31	<0.001†
SN/GoGn	27.84 ± 4.25	30.77 ± 4.60	2.93 ± 2.09	<0.001‡
SN/PP	5.33 ± 2.87	5.20 ± 3.59	−0.13 ± 2.73	0.823†
U1/PP	115.38 ± 6.12	115.88 ± 6.25	0.50 ± 2.51	0.361†
IMPA	89.30 ± 6.35	86.75 ± 7.94	−2.55 ± 3.37	<0.001‡
A-Na perp	−2.82 ± 2.25	−0.73 ± 1.99	2.09 ± 2.47	<0.001‡
Pog-Na perp	−0.37 ± 4.11	−2.25 ± 6.54	−1.88 ± 5.62	0.006‡
SN/OccP	10.93 ± 3.93	13.06 ± 4.24	2.12 ± 3.57	0.003‡
Overjet	−3.04 ± 1.20	2.66 ± 3.64	5.70 ± 3.15	<0.001†
Overbite	3.13 ± 2.09	1.58 ± 2.06	−1.55 ± 2.16	0.002†

Note. Data are presented as mean ± standard deviation.
†Paired samples *t* test; ‡Wilcoxon sign rank test.

Table II. Posteroanterior cephalometric changes after RME and FM therapy

Parameters	*T0*	*T3*	*Difference*	P *values*†
Um	54.94 ± 3.06	57.80 ± 3.50	2.44 ± 1.22	<0.001
Uim	0.93 ± 0.81	2.74 ± 1.58	1.79 ± 1.31	<0.001
Uia	6.97 ± 1.36	8.66 ± 1.85	1.58 ± 1.30	<0.001
Lm	54.25 ± 2.57	55.24 ± 2.33	0.98 ± 0.82	<0.001

Note. Data are presented as mean ± standard deviation.
Um, maxillary molar (the most prominent lateral point on the buccal surface of the maxillary first molar); *Uim,* maxillary incisor mesial (the most mesial point of the maxillary central incisor crown); *Uia,* maxillary incisor apex (the most prominent lateral point on the buccal surface of the mandibular first molar); *Lm,* mandibular molar (the most prominent lateral point on the buccal surface of the mandibular first molar).
†Results of paired samples *t* test.

500 g of force per side for at least 16 h/d. The elastics were positioned to create a 30° angle with the occlusal plane, ensuring that the force direction passed near the center of resistance of the nasomaxillary complex. This configuration aimed to minimize the counterclockwise rotation of the maxilla.

As with any study involving removable appliances, patient compliance with the orthodontist's instructions may have varied; however, overall cooperation was generally satisfactory. The subjects achieved an overcorrection to a slight Class II relationship, with all exhibiting a positive overjet. The RME and FM therapy lasted approximately 7-8 months. Lateral and posteroanterior[19] cephalometric radiographs were taken before (T0) and after (T3) treatment and traced using Ceph Tracing software (version 11.0; Dolphin Imaging and Management Solutions, Chatsworth, Calif) to assess sagittal (Table I) and transversal (Table II) changes, respectively.

Speech recordings and analysis

Speech sound evaluation included an articulation test and objective acoustic analysis. The acoustic analysis was conducted on the initial speech evaluation recordings of the subjects at 4 time points: immediately before the RME appliance was applied (T0), 2 weeks later (T1, immediately before FM application), 3 months later (T2), and 1 week after the end of treatment (T3). Speech and language therapists (H.F.K. and B.N.D.) evaluated speech sound disorders. The Articulation Subtest of the Turkish Articulation and Phonology Test, a standardized assessment, was used to evaluate speech sound production.[20] An oral-motor examination was conducted to assess the structures and functions involved in articulation. After these assessments, the acoustic analysis was performed.

Throughout the speech evaluation process, voice and video recordings of the subjects were captured by the speech and language therapist (H.F.K.) in a dedicated recording room specifically designed for voice recording within the Faculty of Dentistry. All procedures were conducted after disinfection, asepsis, and antisepsis protocols. Word productions were digitally recorded directly to a laptop's hard drive using a Shure SM58 microphone. During the recording, subjects sat in an upright position, with the microphone positioned approximately 15-20 cm from their

Table III. Evaluation of acoustic data of the /s/

Variables	Time points				Statistical evaluations						
	T0	T1	T2	T3	η^2p or χ^2	Overall	T0-T1	T0-T2	T0-T3	T1-T2	T1-T3	T2-T3
/s/ initial												
Duration	0.123 (0.108, 0.133)	0.105 (0.096, 0.116)	0.116 (0.102, 0.121)	0.112 (0.098, 0.125)	15.2	0.002†	<0.001	0.011	0.016	0.094	0.072	0.896
Spectral peak	7388.187 (6519.931, 8293.342)	4690.624 (3809.831, 6177.314)	5930.708 (5149.536, 6379.486)	6323.861 (5414.460, 7938.967)	25.3	<0.001†	<0.001	<0.001	0.115	0.313	<0.001	0.005
Center of gravity	7748.229 ± 1274.874	4251.886 ± 2627.895	4189.814 ± 1505.419	5661.714 ± 1702.208	0.368	<0.001†	0.004	<0.001	0.029	0.999	0.271	0.022
F2 Transition	7378.964 (6980.696, 7855.064)	7722.672 (7173.573/8370.446)	7633.402 (6967.665, 8104.360)	7688.489 (7126.606, 8208.909)	6.65	0.084†	0.060	0.233	0.154	0.154	0.233	0.811
/s/ final												
Duration	0.098 (0.081, 0.127)	0.097 (0.089, 0.112)	0.107 (0.088, 0.116)	0.093 (0.080, 0.112)	1.69	0.639†	0.908	0.565	0.491	0.645	0.422	0.208
Spectral Peak	6896.164 ± 1599.231	4759.790 ± 1895.716	5380.557 ± 1627.671	6210.369 ± 1556.405	0.303	<0.001†	<0.001	0.003	0.345	0.522	0.026	0.290
Center of Gravity	7106.782 ± 1156.797	3958.474 ± 1767.770	4138.638 ± 2247.186	5472.934 ± 1740.214	0.467	<0.001†	<0.001	<0.001	<0.001	0.987	0.032	0.098
F2 Transition	7892.917 (7667.806, 8473.293)	8091.013 (7708.106/8699.882)	8035.273 (7123.017, 8546.174)	8278.909 (7912.595, 8431.993)	1.85	0.603†	0.252	0.818	1.000	0.358	0.252	0.818
/s/ total												
Duration	0.109 (0.096, 0.133)	0.099 (0.092/0.113)	0.110 (0.099, 0.121)	0.103 (0.091, 0.119)	6.65	0.084†	0.060	0.233	0.154	0.154	0.233	0.811
Spectral peak	7186.241 ± 1308.094	4752.719 ± 1510.016	5517.919 ± 1176.014	6384.383 ± 1312.853	0.449	<0.001†	<0.001	<0.001	0.127	0.149	<0.001	0.060
Center of gravity	4752.719 ± 1510.016	5567.324 ± 1661.690	7277.506 ± 1152.782	4164.227 ± 1741.111	0.490	<0.001†	<0.001	<0.001	0.001	0.999	0.091	0.034
F2 Transition	7757.388 (7381.069, 8085.124)	7963.415 (7811.941/8580.441)	7762.088 (7352.615, 8251.516)	7981.646 (7654.769, 8228.377)	3.55	0.315†	0.065	0.295	0.415	0.415	0.295	0.815

Note. Data are presented as median (25th, 75th percentiles) for the Friedman test and χ^2, and mean ± standard deviation and η^2p for repeated measures analysis of variance.
†Friedman test; ‡Repeated measures analysis of variance.

mouths. The recordings were made at a sampling rate of 44.1 kHz (16-bit quantization, 22 kHz low-pass filter). The subjects were instructed to read word lists at a comfortable pitch and volume, maintaining a normal speaking rate.

The test words consisted of 12 monosyllabic words containing the 3 Turkish corner vowels /ʌ, i, and u/ in monosyllabic (consonant-vowel-consonant) structures. These included /sʌtʃ/, /sis/, and /sutʃ/ for initial /s/ sounds; /tʌs/, /pis/, and /kus/ for final /s/ sounds; /ʃut/, /ʃiʃ/, and /ʃʌt/ for initial /ʃ/ sounds; and /kʌʃ/, /diʃ/, and /kuʃ/ for final /ʃ/ sounds. When selecting test words, special attention was given to the phonetic context in which the vowels occurred, ensuring that all Turkish corner vowels were preceded and followed by voiceless obstruents (stops and/or fricatives). All the test words were real and familiar to children, and they were designed to elicit the target vowels and sibilant sounds /s/ and /ʃ/. Five randomized lists of target and distractor words were created, with each list arranged to include 2 distractor words at the beginning and end of each column. This arrangement aimed to minimize the effects of different reading tendencies and intonation variations that subjects may exhibit when starting the list, transitioning between columns, or reaching the end of the list. Moreover, 3 of the 5 lists (second, third, and fourth) were subjected to acoustic analysis. The subjects were asked to read the words in a carrier sentence, 'Oya ….. oku' ('Oya, read …'). The randomization of words produced 5 lists in total. A total of 12,672 tokens (12 sounds × 4 parameters × 3 repetitions × 22 subjects × 4 time points) were analyzed across the study periods (T0, T1, T2, and T3).

Reliability of sound recordings

Speech analyses were conducted using Praat software version 6.1.27 (Paul Boersma & David Weenink, University of Amsterdam, Netherlands) in a computer-based environment by the same speech and language therapist (B.N.D). Each word was repeated 5 times within the context of the designated sentence. For reliability, sound recordings from the first and fifth repetitions were excluded from the analysis. Formant frequencies were evaluated based on the second, third, and fourth repetitions (Tables III and IV). To ensure the accuracy of the acoustic analysis, all speech samples were preprocessed using a high-pass filter to remove any low-frequency noise <100 Hz. The analysis focused on the key formant frequencies of the fricative sounds (/s/ and /ʃ/), particularly the onset frequency of F2. In addition to F2, the spectral peak location and the center of gravity within the 2.0-2.5 kHz frequency range were also analyzed.[21]

Table IV. Evaluation of acoustic data of the /ʃ/

Variables	Time points				Statistical evaluations						
	T0	T1	T2	T3	η^2p or χ^2	Overall	T0-T1	T0-T2	T0-T3	T1-T2	T1-T3	T2-T3
/ʃ/ initial												
Duration	0.130 (0.111, 0.142)	0.105 (0.097, 0.119)	0.115 (0.103, 0.129)	0.117 (0.104, 0.133)	15.3	0.002†	<0.001	0.026	0.057	0.042	0.019	0.739
Spectral peak	4096.600 ± 968.319	3234.341 ± 872.373	3568.124 ± 930.503	3901.307 ± 955.713	0.230	0.007‡	0.009	0.131	0.606	0.253	0.048	0.472
Center of gravity	4726.347 ± 787.934	3124.794 ± 996.244	3074.427 ± 1191.342	4229.085 ± 865.221	0.497	<0.001†	<0.001	<0.001	0.028	0.997	0.002	0.004
F2 transition	6924.408 (6487.040, 7346.634)	6681.037 (6413.148, 7361.717)	6596.802 (6157.316, 7278.533)	6819.988 (6221.308, 7401.597)	1.53	0.676†	0.818	0.359	0.818	0.253	0.646	0.491
/ʃ/ final												
Duration	0.105 (0.089, 0.118)	0.108 (0.102, 0.116)	0.111 (0.095, 0.118)	0.099 (0.091, 0.122)	5.96	0.179†	0.051	0.093	0.082	0.505	0.545	0.952
Spectral peak	4025.815 (3491.204, 4551.222)	3532.425 (2614.691, 3801.659)	3475.140 (3221.342, 4364.932)	3953.939 (3461.233, 4412.690)	16.9	<0.001†	<0.001	0.038	0.599	0.038	<0.001	0.117
Center of gravity	4879.221 (4439.841, 5401.619)	2967.099 (2481.580, 4255.110)	3523.555 (2296.632, 4379.021)	4324.573 (3748.037, 4942.787)	28.5	<0.001†	<0.001	<0.001	0.018	0.367	<0.001	0.005
F2 transition	7261.037 (6739.842, 7704.597)	6958.854 (6327.632, 7362.420)	6665.519 (6375.346, 7269.785)	7056.287 (6589.928, 7936.870)	35.6	<0.001†	<0.001	<0.001	<0.001	0.098	0.504	0.022
/ʃ/ total												
Duration	0.116 (0.100, 0.125)	0.107 (0.100, 0.116)	0.111 (0.098, 0.125)	0.112 (0.102, 0.125)	7.36	0.806†	0.153	0.280	0.263	0.151	0.780	0.280
Spectral peak	4109.628 ± 872.393	3307.891 ± 982.204	3665.597 ± 875.320	3966.716 ± 742.860	0.449	0.007‡	<0.001	<0.001	0.127	0.129	<0.001	0.060
Center of gravity	4763.935 (4300.223, 5268.597)	3088.784 (2571.638, 3829.361)	3405.008 (2451.623, 3870.715)	4253.597 (3725.184, 4773.043)	33.3	<0.001†	<0.001	<0.001	<0.001	0.200	<0.001	0.027
F2 transition	7043.065 (6734.789, 7616.236)	6882.450 (6463.845, 7410.073)	6695.227 (6492.743, 7043.085)	6877.403 (6482.556, 7728.811)	3.55	0.135†	0.065	0.295	0.415	0.415	0.295	0.815

Note. Data are presented as median (25th, 75th percentiles) for the Friedman test and χ^2, and mean ± standard deviation and η^2p for repeated measures analysis of variance.
†Friedman test; ‡Repeated measures analysis of variance.

Acoustic evaluation parameters

The fricative offset was defined as the onset of vowel periodicity. The onset and offset of the fricative were determined using the waveform and wideband spectrogram.[22,23]

The spectral peak of each fricative was identified by calculating the fast Fourier transform (FFT) power spectrum, which analyzes the frequency components of a signal. The FFT was computed using a 1024-point frame, corresponding to a window of approximately 46 milliseconds (ms) at a sample rate of 22.05 kHz. This window was centered on the midpoint of each fricative to represent the steady-state properties of the sound accurately. The spectral peak was identified as the frequency with the highest amplitude in the FFT spectrum, representing the dominant resonant frequency of the fricative sound.

Linear predictive coding was employed to estimate resonance frequencies (formants) from the speech signal, simulating the vocal tract and enabling precise identification of the onset frequency of F2 and other formant frequencies. A 512-point frame (approximately 23 ms) was used to ensure that the measurement corresponded to the brief duration required for articulatory transitions in natural speech, accurately representing the onset frequency of F2 during this transitional phase.

The FFT was calculated using a 46-ms full Hamming window centered on the midpoint of the fricative, capturing the spectral mean of the sound.

Perceptual evaluation of speech

Three experienced speech-language pathologists conducted the perceptual evaluation of speech. Audio recordings of a carrier sentence and 1 minute of spontaneous speech from the T0, T2, and T3 time points were presented to listeners randomly and anonymously. The listeners assessed the production accuracy of the /s/ total and /ʃ/ total phonemes and overall intelligibility using a linear scale ranging from 0 (completely accurate) to 10 (completely inaccurate)[24] (Table V). The evaluation was conducted via Google Forms, and the results were calculated by averaging the scores obtained for each subject.

Statistical analysis

The collected data were recorded using Microsoft Excel (Office 365; Microsoft, Redmond, Wash) and statistically analyzed using Jamovi software (version 2.4.8; The Jamovi Project, Sydney, Australia). The data were assessed for normality using the Shapiro-Wilk test and homogeneity using Levene's test. Parametric variables

Table V. Perceptual evaluation score comparisons.

	Time points			Statistical evaluations				
Variables	*T0*	*T2*	*T3*	*Overall*†	χ^2	*T0-T2*	*T0-T3*	*T2-T3*
/s/ total average score	2.00 (1.67/3.00)[a]	3.67 (3.00/4.67)[b]	1.33 (1.00/1.67)[c]	<0.001	24.30	<0.001	<0.001	<0.001
/ʃ/ total average score	2.00 (1.67/2.33)[a]	3.67 (2.67/4.33)[b]	1.33 (1.00/1.67)[c]	<0.001	31.92	<0.001	<0.001	<0.001
Overall intelligibility score	2.00 (2.00/2.67)[a]	4.00 (3.33/4.33)[b]	1.33 (1.00/1.67)[c]	<0.001	28.27	<0.001	<0.001	<0.001

Note. Data are presented as median (25th, 75th percentiles) and χ^2; 0-3, high accuracy; 4-6, moderate accuracy; 7-10, low accuracy. Similar superscripted letters within a row indicate similarity between time points, whereas different letters indicate difference between time points.
†Results of the Friedman test.

are presented as the mean ± standard deviation and were compared across time points using repeated measures analysis of variance, followed by post-hoc pairwise Tukey's tests. Nonparametric variables are reported as the median (interquartile range) and were compared across time points using the Friedman test, followed by post-hoc pairwise Durbin-Conover tests. For cephalometric changes, parametric variables were compared using the paired samples *t* test, and nonparametric variables were compared using the Wilcoxon signed rank test. A $P < 0.05$ was considered statistically significant.

Method error

To assess methodological error, the lateral and posteroanterior cephalometric measurements were retraced for 10 subjects by the same orthodontist (N.H.) 3 months after the initial measurements. The relationship between the first and second measurements was evaluated using the intraclass correlation coefficient. Cronbach α was 0.966 (95% confidence interval, 0.923-0.986), indicating excellent reliability between them, and a paired samples *t* test comparing them was nonsignificant ($P = 0.876$), suggesting no statistically significant difference between the initial and repeated measurements. The consistency between the speech-language pathologists who performed the perceptual evaluations was assessed using the intraclass correlation coefficient. Cronbach α was 0.786 (95% confidence interval, 0.742-0.856), and pairwise paired samples *t* tests were nonsignificant ($P < 0.05$).

RESULTS

The lateral cephalometric changes observed after RME and FM therapy are summarized in Table I. The SNA ($P < 0.001$), ANB ($P < 0.001$), SN/GoGn ($P < 0.001$), A-Na perp ($P < 0.001$), SN/OccP ($P = 0.003$), and overjet ($P < 0.001$) increased significantly, whereas the SNB ($P < 0.001$), IMPA ($P < 0.001$), Pog-Na perp ($P = 0.006$), and overbite ($P = 0.002$) decreased significantly. The posteroanterior cephalometric changes observed after RME and FM therapy are summarized in Table II. The maxillary molar (Um, $P < 0.001$), maxillary incisor mesial (Uim, $P < 0.001$), maxillary incisor apex (Uia, $P < 0.001$), and mandibular molar (Lm, $P < 0.001$) increased significantly.

The evaluation of the /s/ sound is presented in Table III (Fig 1). For words in which /s/ occurred at the beginning, significant differences were observed across time points in duration ($P = 0.002$), spectral peak ($P < 0.001$), and center of gravity ($P < 0.001$). The duration was significantly shorter after treatment compared with before treatment. Although the spectral peak decreased significantly during treatment, its value at the end of treatment was similar to its initial value. The center of gravity decreased significantly during treatment and was significantly lower at the end of treatment compared with before treatment.

For words in which /s/ occurred at the end, significant differences were observed across time points in the spectral peak ($P < 0.001$) and center of gravity ($P < 0.001$). The spectral peak decreased significantly during treatment but returned to a value similar to its initial value. The center of gravity also decreased significantly during treatment but increased slightly at the end, although remaining significantly lower than its initial value.

For works in which /s/ occurred at both the beginning and end (total), significant differences were observed across time points in the spectral peak ($P < 0.001$) and center of gravity ($P < 0.001$). Both parameters decreased significantly during treatment and showed some improvement by the end of treatment; however, their values remained significantly lower than their initial values.

The evaluation of the /ʃ/ sound is presented in Table IV (Fig 2). For words in which /ʃ/ occurred at the beginning, significant differences were observed across time points in duration ($P = 0.002$), spectral peak ($P = 0.007$), and center of gravity ($P < 0.001$). The duration and spectral peak decreased significantly during treatment but returned to values close to their initial values

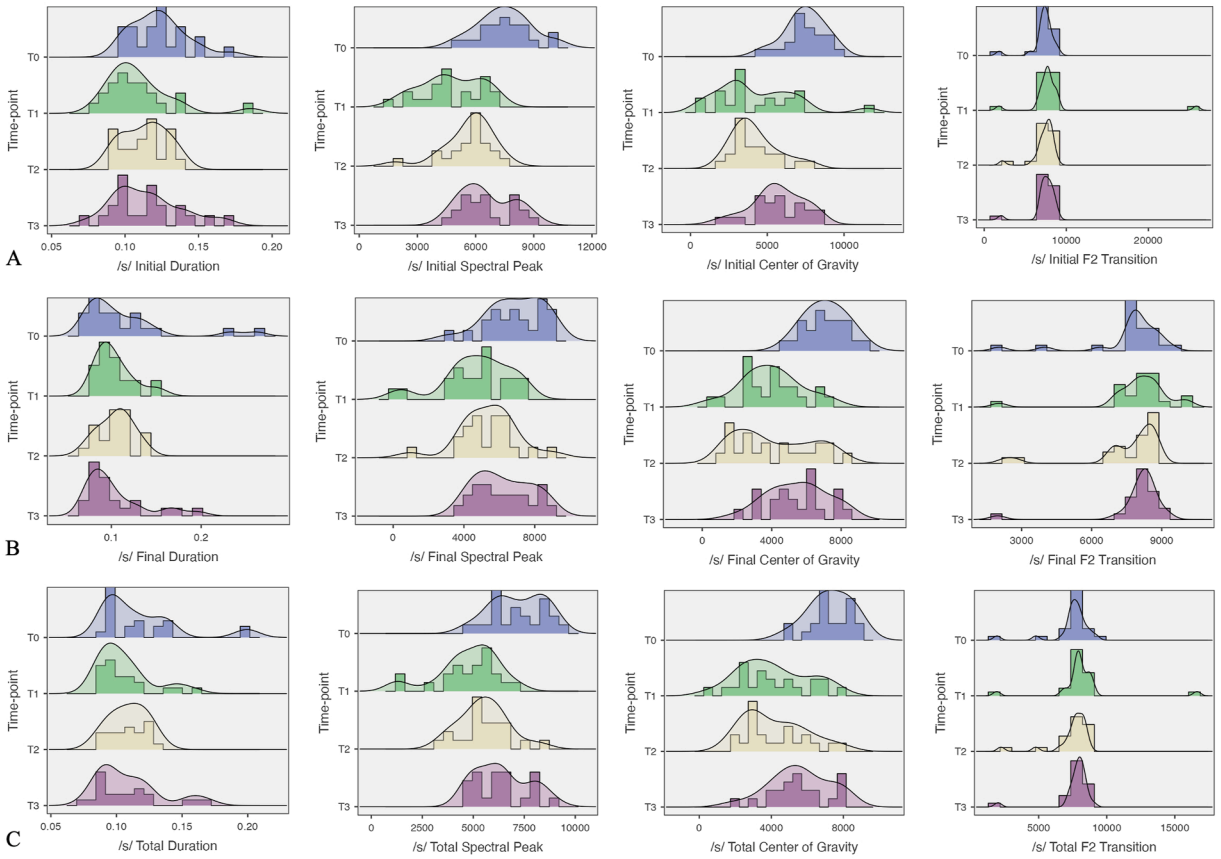


Fig 1. A, Graphical representation of acoustic parameters taken in the initial period for /s/; **B,** Graphical representation of acoustic parameters taken in the final period for /s/; **C,** Graphical representation of acoustic parameters taken for the total of periods for /s/.

by the end of treatment. The center of gravity decreased significantly during treatment but then increased by the end of treatment, although remaining significantly lower than its initial value.

For words in which /ʃ/ occurred at the end, significant differences were observed across time points in the spectral peak (P <0.001), center of gravity (P <0.001), and F2 transition (P <0.001). The spectral peak and F2 transition decreased significantly during treatment but returned to values close to their initial values by the end of treatment. The center of gravity decreased significantly during treatment but then increased by the end of treatment, although remaining significantly lower than its initial value.

For words in which /ʃ/ occurred at both the beginning and end (total), significant differences were observed across time points in the spectral peak (P <0.001) and center of gravity (P <0.001). The spectral peak decreased significantly during treatment but returned to a value close to its initial value by the end of treatment. The center of gravity decreased significantly during treatment but then increased by the end of therapy, although remaining significantly lower than its initial value.

Table V presents the average scores for the fricative sounds /s/ total and /ʃ/ total as well as overall intelligibility across perceptual evaluations by 3 different speech-language pathologists at 3 different time points: T0, T2, and T3. At T0, perceptual evaluation scores indicated high articulation accuracy. At T2, the scores were significantly higher than at T0 (P <0.001), indicating a decrease in articulation accuracy. At T3, the scores were significantly lower than at both T0 and T2 (P <0.001), indicating a significant improvement in articulation accuracy. The differences between all-time points are statistically significant (P <0.001).

DISCUSSION

Malocclusion can affect oral-motor control, resulting in speech difficulties.[25,26] This study aimed to

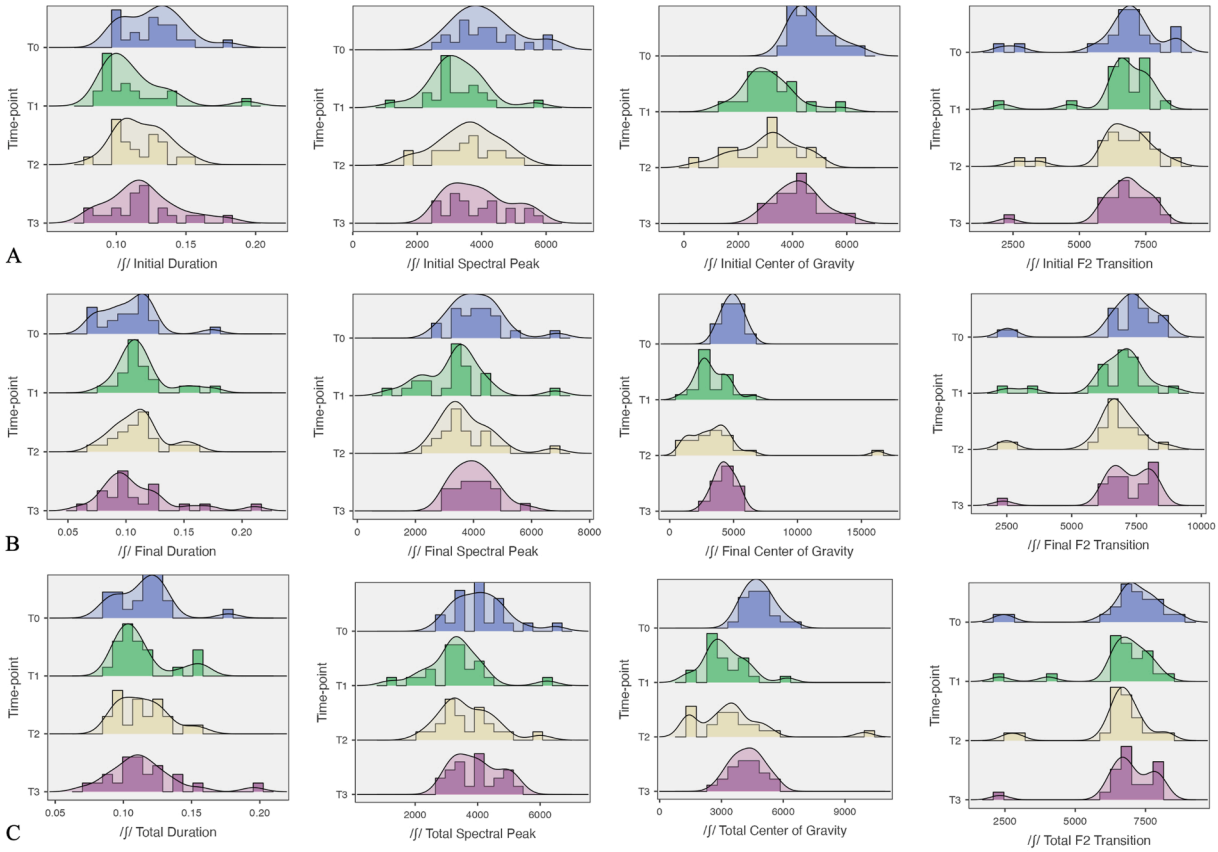


Fig 2. **A**, Graphical representation of acoustic parameters taken in the initial period for /ʃ/; **B,** Graphical representation of acoustic parameters taken in the final period for /ʃ/; **C,** Graphical representation of acoustic parameters taken for the total of periods for /ʃ/.

evaluate the effect of RME and FM therapy of Class III malocclusion on the acoustic properties of fricative sounds (/s/ and /ʃ/). Therefore, the correct production of other phonemes in Turkish was assessed using the Articulation Subtest. Children with incorrect productions of phonemes, such as /r, k, and g/, were excluded from this study, as incorrect productions could alter the acoustic properties of other sounds within words. Target words for evaluating the acoustic properties of target sounds were presented in a carrier sentence. This study provides insights into the physiological relationship between correcting abnormally positioned jaws and teeth and sound articulation. Its results also elucidate how speech is influenced by correcting skeletal discrepancies, specifically by eliminating orthodontic malocclusion.

Studies have shown that orthodontic treatments can temporarily alter fricative acoustics by modifying the spatial configuration of the oral cavity, thereby affecting parameters such as the center of gravity, spectral moments, and amplitude. It is well-established that speech is immediately impaired, particularly in fricatives, after the placement of a Hyrax appliance, with normalization extending up to a couple of months after its removal.[27] This pattern has also been observed with palatal expanders, Hawley retainers, and lingual appliances.[28] The consensus in the literature suggests that speech typically returns to normal within 1-3 months.[27–29] These treatments particularly influence the production of fricative sounds such as /s/, /z/, /ʃ/, and /ʒ/, which require precise articulatory positioning and controlled airflow.[1,26] Although speech difficulties involving other sounds often resolve within weeks, challenges with fricative sounds may persist for >3 months.[28]

The reasons for selecting fricative sounds (/s/ and /ʃ/) in this study were as follows. First, no comprehensive study has yet described changes in the acoustic properties of fricative sounds after RME and FM therapy. Second, RME and FM therapy may alter the sagittal

distance in the sound production area, and maxillary expansion may change the production location and acoustic properties of these sounds. Third, /s/ has been reported as the sound most frequently impacted by orthodontic treatments that modify the alveolar and palatal regions.[26] Furthermore, acoustic measurements such as duration, spectral peak, the center of gravity, and formant frequency were chosen because these parameters provide numerical insights into the effectiveness of the procedures and play a critical role in characterizing fricatives.[27]

Because malocclusion can affect sound production at multiple levels, analyzing individual sounds is essential for understanding the treatment's impact on each specific sound.[30] Such studies can also inform speech-language pathologists in planning target selection and tailoring intervention strategies to meet the treatment-specific needs of patients with malocclusion. Although the cephalometric changes observed with RME and FM therapy in our study differ from those reported in other studies because of variations in factors such as subject age, RME appliance or FM type, expansion protocols, applied forces, and treatment duration, our findings are generally consistent with the existing literature.[31,32]

Duration (in ms) is a fundamental feature used to describe sound and represents the basic temporal measurement of speech. Duration data provide insights into speech production, perception, and phonological theory.[33] Syllable position influences the duration, spectral peak, center of gravity, and F2 transitions of /s/ and /ʃ/ sounds in adults.[29] Posttreatment changes in closure may create ambiguity in short-duration fricatives at the end of words, making word-final sounds more susceptible to alterations in speech acoustics.[34] In our study, when the acoustic values of /s/ and /ʃ/ sounds were compared across word positions, significant decreases were observed in the center of gravity and spectral peak for all positions. However, a significant decrease in duration was observed only in the word-initial position. This decrease in word-initial duration aligns with previous findings, suggesting that word-initial sounds are more sensitive because of their prominence in speech perception.[35] Some studies suggest that gender is not a distinguishing factor for the duration of target sibilant sounds and that no significant difference exists between males and females for the /s/ and /ʃ/ sounds.[36,37] Similarly, our study found no significant difference in duration between males and females. Conversely, other studies have indicated that durations tend to be longer in females than in males, with this difference being most pronounced in /s/ and /ʃ/ sounds.[21,38] The longer duration observed in females was interpreted as a language-specific characteristic.

A spectrograph is a device that visualizes speech sounds and produces a representation called a spectrogram. A sound spectrogram is one of the most fundamental tools for acoustic speech analysis, providing a visual representation of the frequency components of sound over time.[1] The spectral peak is observed as regions of energy density and peaks in the spectrogram. Although the spectral peak value for /ʃ/ decreased during treatment at both word-initial and word-final positions, it was generally not significantly affected by treatment. When evaluated in total, /s/ was produced at significantly lower spectral peak values compared with before treatment, although these values remained higher than those for /ʃ/. These findings align with those of a previous study showing that spectral peak values decrease as the place of articulation moves further back.[23] Notably, the spectral values reported in that study (6839 Hz for /s/ and 3820 Hz for /ʃ/) are close to the values observed at the end of treatment in our study, despite differences in the subjects' native language. Notably, while spectral values are reported, factors such as regional dialect, gender, socioeconomic class, and language background may also influence variations in the spectral measurements of sibilants.[39]

The center of gravity, representing the average energy distribution, is a reliable indicator of the place of articulation for fricatives, making it a key characteristic. It is expected to remain relatively stable across realizations of the same sound.[23] In our study, the center of gravity decreased during treatment for both /s/ and /ʃ/ in word-initial and word-final positions and overall. The significant decreases observed in duration, spectral peak, and center of gravity for /s/ and /ʃ/ during orthodontic treatment highlight the impact of the intervention on the acoustic properties and articulation of these sounds. Class III malocclusion, characterized by an anteriorly positioned lower jaw, can affect the contact of the tongue with the maxillary teeth, making it challenging to produce high-frequency fricative sounds, especially /s/ and /ʃ/.[1,27] Treatment for Class III malocclusion allows the tongue to adopt a more favorable position for producing fricative sounds and enables a more harmonious direction of intraoral airflow, thereby reducing the time and energy needed to produce these sounds.[40]

When the changes in /s/ and /ʃ/ during the orthodontic treatment process were analyzed, a sudden decrease in the spectral peak and center of gravity was observed immediately after the placement of the RME appliance. These findings align with those of previous studies,[27,41] which also reported that the placement of an orthodontic appliance caused an abrupt reduction in spectral peak values. The placement of the RME appliance led

to this behavior in both fricative sounds, followed by a gradual increase in spectral peak values throughout treatment. However, these values were significantly lower at the end of treatment than before treatment. As noted in the literature, maxillary expansion is expected to increase palatal volume, thereby lowering the frequency.[27,41] In summary, the observed decrease in the center of gravity and spectral peak across all positions, as well as the reduced duration in word-initial positions, indicates that orthodontic treatment not only affects the articulatory positioning and resonance properties of fricatives but also enhances articulatory accuracy. These findings are consistent with those of studies showing that structural changes in the oral cavity can positively influence the acoustic stability and efficiency of fricatives.[34,40]

In phonetics, the values of first (F1), second (F2), third (F3), and fourth (F4) formants differ for vowels and voiced consonants. F1 represents the lowest-frequency formant, followed by F2, F3, and F4. Formant frequencies (measured in Hz) typically range 0-5000 Hz. F1 and F2 correspond to the location of vowel articulation within the mouth, whereas F3 and F4 reflect vocal characteristics such as tone.[27] In speech acoustics, the onset frequency of F2 provides insight into the horizontal position of the tongue, particularly during transitions between vowels and consonants.[42] Tongue positioning often differs between patients with Class III malocclusion and ostensibly healthy subjects, and they may produce sounds with compensatory articulation gestures, such as the tongue contacting the incisors instead of the alveolar ridge for sibilants /s/and /z/,[43] which can result in atypical F2 transition patterns. Our study observed no significant changes in F2 values for /s/ and /ʃ/ after RME and FM therapy. These findings suggest that although the bite was corrected through orthodontic treatment, tongue position likely remained unchanged. Alterations in physical structures, such as those achieved through motor commands and orthognathic or orthodontic interventions, may not immediately modify established articulatory behaviors.[44] In such instances, speech and language therapy is recommended to address habitual motor patterns and improve articulatory accuracy.

The fact that perceptual evaluation results at T2 were lower than those at T0 and T3 indicates the presence of a temporary adaptation process. It is well known that orthodontic treatment induces significant changes in anatomic structures, such as jaw position and dental alignment, which necessitate the reorganization of articulators and the development of new motor control strategies during speech production. Because this process takes time, the deterioration observed at T2 can be interpreted as a reflection of a temporary adaptation period, which is a normal part of the treatment process and not a cause for concern.

The perceptual evaluation results at T3 returned to or were lower than those at T0, suggesting that subjects not only adapted to the new anatomic structure within a week after RME and FM therapy but also exhibited improved articulation accuracy. This finding suggests that posttreatment speech mechanisms undergo long-term reorganization and that the adverse effects of the treatment are not permanent.[42,45] Notably, the consistency of T3 results, contrasting with the deterioration observed at T2, confirms that the adaptation process was completed successfully and that the speech organs have effectively adjusted to the new structure.

Limitations

The main limitation of our study was the lack of a control group, as it would have been unethical to withhold RME and FM therapy from patients requiring it for their Class III malocclusion. To address this limitation, in our study, we assessed speech development through perceptual analyses, which, although subjective, provided meaningful insights. However, future studies could incorporate a control group to provide more comprehensive and objective findings by reducing confounding variables and enhancing reliability. The other limitations of our study include its small sample size, inclusion of monolingual patients, and short follow-up period. Conducting the final measurement just 1 week after appliance removal may be premature, as the residual effects of the bulky rapid maxillary expander may still influence speech.

Although an increase in correct production was noted in word-initial positions after treatment, no significant difference was observed in word-final positions. This difference can be explained by the tendency of patients to maintain their habitual motor patterns despite the normalization of their articulation structures. However, the change in the production of target sounds at the beginning of a word may be attributed to the greater awareness and motor control of sounds in this position compared with others.[46] The change in the production of target sounds at the beginning of the word can also be explained by coarticulation. Although sounds at the beginning of the word are generally less affected by the motor production of surrounding sounds, sounds within and at the end are more influenced by intense coarticulation.[47] This difference may lead patients to maintain their habitual motor patterns in word-initial and word-final positions, even if their articulation structures are normalized. Speech and language therapy is recommended to ensure the correct

production of target sounds in other syllable positions and during speech.

We anticipate that orthodontic therapy, which reduces the duration and frequency of target sounds, will improve speech intelligibility by preserving essential phonetic characteristics. The literature[27,29] highlights that correcting malocclusion enhances esthetic appearance and improves functional sound production. Therefore, changes in acoustic characteristics after orthodontic treatment suggest a positive impact on speech acoustics in the early period. These findings can assist clinicians in addressing speech-related concerns throughout orthodontic treatment, guiding speech and language therapist assessments, and optimizing target selection for speech sound disorders.

Our study demonstrated that correcting Class III malocclusion through RME and FM therapy significantly impacted the acoustic properties of fricative sounds (/s/ and /ʃ/). These results suggest that orthodontic treatment can improve facial esthetics and enhance speech intelligibility, particularly in terms of articulation precision. They emphasize the need for speech-language pathologists to actively monitor speech changes throughout orthodontic treatment. The persistence of specific articulation errors after treatment also underscores the importance of incorporating targeted speech therapy to further refine articulation. Therefore, collaboration between orthodontists and speech-language pathologists is crucial to ensure the best possible speech outcomes for patients undergoing RME and FM therapy.

CONCLUSIONS

Our findings indicate that the pretreatment and posttreatment acoustic properties of /s/ and /ʃ/ sounds exhibit similar changes, suggesting that the treatment affects both sounds similarly. The significant decreases in the spectral peak and center of gravity of /s/ and /ʃ/, as well as changes in the maxillary and mandibular structures, because of the RME and FM therapy, highlight its positive impact on the acoustic properties of these sounds. Therefore, the null hypothesis was rejected. In word-initial positions, duration significantly decreased as correct production increased, enhancing intelligibility. However, no significant difference was observed in word-final positions.

The lower perceptual evaluation scores (subjective data) and the favorable changes in the acoustic properties of the /s/ and /ʃ/ sounds (objective data) after RME and FM therapy indicate that patients not only adapted to the new anatomic structure but also exhibited improved articulation accuracy. However, errors in the articulation of the target sounds remained, and 100% accuracy in articulation was not achieved. It should also be noted that patients may experience speech deterioration during RME and FM therapy, which can be observed up to the third month.

AUTHOR CREDIT STATEMENT

Gokhan Coban contributed to conceptualization, methodology, validation, investigation, resources, data curation, writing of original draft, writing - review and editing, supervision, and project administration. Nisa Gul Amuk contributed to conceptualization, methodology, investigation, resources, data curation, and supervision. Beyza Nur Dukar contributed to methodology, software, validation, formal analysis, investigation, data curation, writing of original draft, and writing - review and editing. Hatice Feyza Konca contributed to conceptualization, methodology, software, validation, and data curation. Nizami Hashimli contributed to methodology, investigation, and data curation. Taner Ozturk contributed to validation, formal analysis, resources, data curation, writing of original draft, and writing - review and editing.

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