Internal derangement of the temporomandibular joint (TMJ) has been defined as an abnormal relationship between the articular disc and the mandibular condyle, fossa, and articular eminence. Clinical signs vary from functional disc displacement to disc dislocation with/without reduction. In the early phase of internal derangement of the TMJ, the articular disc becomes displaced from its original position, and the posterior border of the disc undergoes a movement to anterior of the condylar head. The disc remains in this position as long as the mouth is closed. While the mouth is opening, the disc is re-situated on the condylar head. The movement of the disc onto and off of the condylar head may result in a clicking (single or reciprocal) sound heard by the patient and/or by the clinician. If this condition persists, another stage of derangement is noted; ie, the rubbing of the degenerated joint surfaces against each other makes a crepitation sound. The etiology of internal derangements is multifactorial, and common symptoms such as pain in the TMJ, restriction in mandibular functional motion, and joint noises motivate the patient to seek treatment.

Over the years, TMJ sounds have received increasing attention as an important physical sign of joint dysfunction and/or pathology. The main drawback related to the pathology of sounds is the difficulty in making accurate comparisons between different observers. Routine recording and measuring of TMJ sounds are carried out...
by the use of microphones,\textsuperscript{9–11} accelerometers,\textsuperscript{12,13} or a combination of microphones and stethoscopes.\textsuperscript{5,14,15} Recently, the development of electronic technology has drawn more and more attention as a method of detecting TMJ functional status with electronic recordings.\textsuperscript{5} Electronic recording of the TMJ sound allows detailed analysis and may provide a more reliable comparison between different examiners and also between different sessions of clinical examinations.\textsuperscript{16,17}

In order to make quantitative description and classification of different TMJ sounds, many studies have been performed.\textsuperscript{11} Recording of TMJ sounds was first reported by Ekensten in 1952.\textsuperscript{18} Ekensten recorded the joint sounds of 30 patients on an oscilloscope and noted the variability of wave patterns. The wave patterns of TMJ sounds were then studied to classify clicking sounds in terms of signal duration, as measured on the analog display.\textsuperscript{19} Watt et al. described waveforms of clicks and crepitus based on the oscilloscopic display of the analog sound recordings.\textsuperscript{20} However, early studies with analysis of the time-amplitude waveforms of TMJ sounds have led to difficulty in characterizing signals based only on their time behavior; therefore, several time-frequency analyses have been developed for the analysis and classification of TMJ sounds.\textsuperscript{3} Widmalm et al. described a new method for time-frequency (TF) analysis, using reduced interference distribution (RID) to classify the sound recordings.\textsuperscript{21} They identified five subclasses and that clicks of RID types 1, 2, and 3 had a few energy peaks close in time, while crepitation of RID types 4 and 5 had multiple energy peaks occurring close in time for a period of 20 to 300 milliseconds. However, RID generally does not present positive energy distribution, making it hard to interpret the resulting distributions.\textsuperscript{3} Akan and Unsal used evolutionary spectrum TF analysis of TMJ sounds and classified the sounds into four main categories: (1) click; (2) coarse crepitation; (3) soft crepitation; and (4) click with crepitus.\textsuperscript{3} Unsal-Basar et al. also used the TF energy distribution of TMJ sounds with the use of evolutionary spectral analysis (ESA) and stated that it was a useful approach to distinguishing TMJ sounds and detecting the early degeneration of patients.\textsuperscript{22} According to TF analysis, it was stated that clicks are identified as high-amplitude peaks of very short duration, and crepitations are signals with multiple peaks of various amplitudes and longer duration, as well as wide frequency signals.\textsuperscript{7,11,19}

An anterior repositioning splint (ARS) is commonly used in the management of patients with internal TMJ derangements for the re-establishment of a normal condyle-disc relationship. The major goal of such treatment is to eliminate joint sounds by recapturing the disc; subsequently, if the disc is recaptured, a smooth, coordinated, painless range of motion can often be obtained. In this way, joint noises and pain could be eliminated.\textsuperscript{23,24} In this respect, Tecco et al. evaluated pain and joint noises using a visual analog scale (VAS) in patients with TMJ internal derangement and found that an ARS could be effective in the treatment of these symptoms because of its capability to immediately re-establish a normal condyle-disc relationship.\textsuperscript{24} Nevertheless, there is no clarity in the complete elimination of TMJ sounds\textsuperscript{24}; some authors stated that the maintenance of a normal condyle-disc relationship was achieved only temporarily with splint therapy and that the sounds could not be eliminated, but their intensity could be reduced.\textsuperscript{23–25}

This study was conducted to determine the efficacy of ARS therapy on the amplitude, duration, frequency range, and energy distributions of electronically recorded TMJ sounds in patients with signs of internal derangement of the TMJ.

**MATERIALS AND METHODS**

**Selection of Patients**

A total of 26 voluntary subjects (21 women and 5 men) aged between 21 and 57 years (mean age 36.4 years) were selected from the Faculty of Dentistry, Gazi University, Turkey, for the present study. All participants were fully informed about the study objective and signed a written consent form approved by the Ethics Committee.

Patients with TMJ pain on palpation on at least one side were included in this study. The subjects who had missing teeth (except for third molars) and complained only of any muscle disorders were excluded. Pregnant patients and patients with psychiatric disorders, systemic conditions, tumors, and/or who had a history of TMJ surgery or temporomandibular disorders (TMD) treatment were excluded. A screening history and clinical examination were performed for each selected patient using the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) Axis I, and the presence of TMJ sounds of the left, right, or both joints was verified with auscultation using a stethoscope. Thus, a total of 44 joints in 26 patients were evaluated (25 left, 19 right). Following the clinical examination and evaluation of TMJ sounds, the type of dysfunction was assessed using the criteria suggested by Okeson.\textsuperscript{26} Accordingly, the patients were classified into three groups: disk displacement (n = 19); disk dislocation with reduction (n = 4); and acute disc dislocation without reduction (n = 3). The patients who reported a history of locked TMJ for a week or less were classified as acute disc dislocation without reduction. Manual manipulation was applied to them to reduce disc dislocation. All of the patients received ARS therapy; however, for the patients with acute disc dislocation without reduction, the splint was applied after manual manipulation.
Construction of Splints
A full-arch maxillary ARS was made for each patient to wear during the night. Initial steps in fabricating a maxillary ARS are identical to those in fabricating a stabilization appliance. An alginate impression (Cavex Holland) was made of the maxillary arch, then poured with a suitable gypsum product (Durone IV, Dentsply), and the cast was obtained. A 2-mm-thick clear resin sheet was adapted to the cast with a pressure adapter (Machine III, Keystone). Then, a small amount of clear autocuring acrylic resin (Duracryl Plus, SpofaDental) was added to the occlusal surface of the anterior portion of the appliances. The anterior stop was constructed, and the appliance was fitted to the maxillary teeth. The anterior stop was constructed, and the anterior position for the splint. Thus, a well-adjusted splint was obtained, allowing contacts on all teeth evenly and simultaneously in the established forward position, and the ramp was developed into a smooth sliding surface so as not to promote catching or locking of the teeth. Care was taken for that position to be the shortest distance from centric relation that eliminated the symptoms. The stop should not significantly increase the vertical dimension. Then, the joint symptoms were evaluated; if no signs and symptoms were noted, this position was verified as the correct anterior position for the splint. Thus, a well-adjusted splint was obtained, allowing contacts on all teeth evenly and simultaneously in the established forward position, and the ramp was developed into a smooth sliding surface so as not to promote catching or locking of the teeth in any position. The splint was smoothly polished. The patients were instructed to wear the splint only at night for 6 weeks. During the treatment period, all participants in the study were instructed not to use any pharmacologic agent.

Recording and Evaluating TMJ Sounds
A specially designed software program and personal computer–linked electrocardiogram (EKG) machine’s signal recording unit (Tepa, Kardiosis) was used to record TMJ sounds. The device was modified with two K-sound microphones (Suntech Medical) with a frequency response up to 1,000 Hz based on Nyquist Theory, in which sampling frequency must be at least twice that of the analog signal. A high-pass filter with a cut-off frequency of 50 Hz was used to suppress artifacts due to respiration and blood flow. This recording system is able to record sounds with a speed of 25 mm/ms through 10,000 ms. During the recording sessions, care was taken to minimize environmental noise, and all recordings were performed in a soundproof room.

During the recordings, the patients sat in an upright position on a chair with no head support to keep the Frankfort plane approximately parallel to the floor. On both the left and right sides of the TMJ, two microphones were fixed on the skin below the ala-tragus line and 1 cm in front of the tragus. All patients were trained regarding the process, including directions pertaining to the amount and speed of the opening and closing cycles, and a trial record was also made for each patient before recordings. Recordings were made bilaterally during three consecutive jaw opening and closing movements. Duration of each opening-closing cycle was about 3 seconds. The recordings were made before occlusal splint therapy and repeated at the 6th week of splint usage.

The spectral analysis of TMJ sounds was made using MATLAB software (MathWorks) with evolutionary spectrum analysis (ESA) of the signal. Evolutionary spectrum is based on a multi-window Gabor expansion to the time-frequency analysis of TMJ sounds. This analysis has been explained in detail previously by Akan and Unsul.

The signals with maximum energy on TF domain graphics were selected in frequency ranges of 0 to 500 per cycle and recorded in joules (J). The change of frequency based on therapy was also identified in the same frequency ranges and recorded as Hz. The maximum amplitude levels were measured in each opening and in each closing cycle in the y axis (dy) and averaged over three opening/closing cycles as millivolts (mV). Similarly, the mean duration of each sound was measured on the x axis (dx) in milliseconds (Fig 1). Then, combining the results of clinical examination and the calculated evolutionary spectra of TMJ sounds, four distinct sound classes were defined as suggested previously (Fig 2): (1) click = very short-duration, high-amplitude peaks; (2) coarse crepitation = short-duration, medium- or high-amplitude peaks in low-frequency range; (3) soft crepitation = long-duration, low-amplitude, multiple peaks that cover whole frequency range; and (4) click with crepitation = short-duration click followed by multiple low-amplitude peaks.

Statistical Analyses
Mean values and standard deviations (SDs) of the amplitude and energy data were calculated using SPSS statistical software program (15.0 version). Comparison of the changes in mean amplitude levels of opening/closing TMJ sounds before and 6 weeks after insertion of splints were analyzed using paired-samples t test. The level of significance was set at 5%.

RESULTS
A total of 26 symptomatic patients (21 women and 5 men, age range 21 to 57 years) were evaluated clinically for the presence of TMJ sounds, and identifiable sounds were detected by auscultation on 44 joints. Of the patients, 7 had only left abnormal sounds, while 1...
The mean amplitude values of the right and left joints before and after splint therapy are listed in Table 2. The opening and closing sounds in both the right and left joints did not show any significant difference in the mean amplitude values before treatment ($P > .05$).

The mean amplitude values in the opening and closing sounds of the right TMJ decreased after treatment for 16 of the 19 patients ($P = .003$, $P = .004$, respectively). In the opening and closing phases, 21 and 17 of the 26 patients with left joint sounds, respectively, showed a decrease in the amplitudes, and the mean amplitude value of both phases showed a statistically significant decrease ($P = .002$; $P = .01$, respectively).

In the time domain graphics, the mean duration of the sounds was recorded as 3 to 32 milliseconds for clicks; 70 to 203 milliseconds for click with crepitation, and 57 to 330 milliseconds for soft crepitation (Table 3). The amount of energy in the frequency range of 0 to 500 Hz was also recorded. The energy contents of the sounds varied from $0.9 \times 10^{-5}$ to $8.9 \times 10^{-5}$, from $2.3 \times 10^{-5}$ to $8.1 \times 10^{-5}$, and from $3.6 \times 10^{-5}$ to $8.9 \times 10^{-5}$ for the clicks, click with crepitation, and soft crepitation, respectively. The total amount of energy values showed a decrease after splint therapy in both of the joints ($P < .05$, Table 2).

The peak frequency in each case could not be specifically determined because of the restriction of the equipment used; however, it varied from 0 to 100 Hz, and the frequency range tested was from 0 to 500 Hz. The percentage of the distribution of the TF range of sound characteristics is listed in Table 3.

Table 1 Distribution of Sound Characterizations According to Evolutionary Spectral Analysis

<table>
<thead>
<tr>
<th></th>
<th>Before treatment (%)</th>
<th>After treatment (%)</th>
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<tbody>
<tr>
<td></td>
<td>Click</td>
<td>Soft crepitation</td>
</tr>
<tr>
<td>Right (n = 19)</td>
<td>84</td>
<td>11</td>
</tr>
<tr>
<td>Left (n = 25)</td>
<td>56</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 2 Mean Amplitude (mV) and Energy ($\times 10^{-5}$ J) Values Before and After Treatment

<table>
<thead>
<tr>
<th></th>
<th>Amplitude</th>
<th>Energy</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Before treatment</td>
<td>After treatment</td>
</tr>
<tr>
<td>Amplitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opening</td>
<td>2.94</td>
<td>1.57</td>
</tr>
<tr>
<td>Closing</td>
<td>2.58</td>
<td>1.15</td>
</tr>
<tr>
<td>Left</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opening</td>
<td>3.78</td>
<td>1.78</td>
</tr>
<tr>
<td>Closing</td>
<td>3.12</td>
<td>1.75</td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>3.89</td>
<td>2.62</td>
</tr>
<tr>
<td>Left</td>
<td>4.22</td>
<td>2.9</td>
</tr>
</tbody>
</table>

*Significant $(P < .05$, paired $t$ test).
Frequencies from 0 to 100 Hz were arbitrarily described as low, from 101 to 300 Hz as middle of the range, and from 301 to 500 Hz as high range, as suggested by Heffez et al.29 The predominant frequency range was between 200 and 500 Hz. The frequency of opening sounds was within the middle to high range, whereas those of closing sounds were within the low to middle range.

DISCUSSION

By using the results of ESA of TMJ sounds before and after therapy, this study determined whether the use of an ARS is efficient in reducing TMJ sounds. Accordingly, for 7 of 19 right joints (37%) and 11 of 25 left joints (44%), it was concluded that therapy was efficient in reducing TMJ sounds.

Joint sounds, pain, and abnormal mandibular movements are frequently reported symptoms in patients with internal derangement of the TMJ; however, these symptoms may also be present in asymptomatic individuals. Therefore, there is a need for objective methods for the recording and classification of TMJ sounds.5 Electronic recording of joint sounds offers several advantages, such as the ability to store and compare observations of different clinical sessions, to record frequencies of the sounds that cannot be perceived by the human ear, to eliminate the differences resulting from the observer, to make objective documentation of the sound, and finally to analyze the recorded signal with regard to amplitude-energy content and TF distribution.30 In the present study, TMJ sounds were visually classified from displayed waveform recordings and subsequently described the qualitative and quantitative characteristics of the sounds.

In order to analyze and classify the TMJ sounds, many TF analysis methods have recently been applied.22 Among these, the Short-Time Fourier Transform (STFT),21–33 the Wigner distribution, and the RID34 have been generally used.21 Widmalm et al21 suggested RID classifications to differentiate sounds indicating different types of pathology. In the present study, for characterizing certain TMJ conditions, the evolutionary spectra of the electronically recorded sounds were applied. This method is based on a multi-window Gabor expansion and is capable of representing narrow-band, wide-band, and time-varying frequency components of a signal with improved TF resolution over the spectrogram.3 This approach has been suggested as an objective tool in clinical practice and is useful in detecting early TMJ degeneration of patients.22

The results showed that the mean amplitude value of both the right and left TMJs was in the range of 0.38 to 9.73 mV. After the use of splints for 6 weeks, the mean amplitude value of both the right and left joints in the opening and closing phases showed a statistically significant decrease. This reduction in mean amplitude values could be related to the improvement of TMJ sounds’ probable morphologic alterations or remodeling in the joint structures over time.

It is not possible to make a direct comparison of these results with those of the previous studies because of methodologic variables. However, there is good agreement with the previous related studies in this field.5,35 Rodrigues et al have analyzed the relationship between joint sounds and TMD severity by electrovibratography and recorded the mean amplitude peaks in patients with TMD as 3.71 ± 7.73 mV and 2.71 ± 3.49 mV for opening and closing, respectively, which were greater than asymptomatic subjects.35 Huang et al have found higher TMJ vibrations in patients with anterior disc displacement with reduction than in the asymptomatic group.5 They concluded that the patients with the TMD signs and symptoms had significantly larger amplitude values during the opening (25.4 ± 12.8 mV) and closing (24.8 ± 10.4 mV) phases. Prinz and Ng recorded TMJ sounds of 238 individuals by placing the microphones in the ear and found peak amplitude values of 80 mV, which are higher than those of the present study.36 These differences could result from the position of the microphones. In the current study, microphones were placed 1 cm in front of the tragus because of easy placement, minimal unwanted effect from mandibular movement, and a relatively small volume of soft tissue between the detector and underlying

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Click (%)</th>
<th>Soft crepitation (%)</th>
<th>Click + crepitation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100</td>
<td>15</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>101–200</td>
<td>22</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>201–300</td>
<td>0</td>
<td>–</td>
<td>40</td>
</tr>
<tr>
<td>301–400</td>
<td>20</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>401–500</td>
<td>26</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>501+</td>
<td>6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0–500</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Time intervals</td>
<td>332</td>
<td>57–330</td>
<td>70–203</td>
</tr>
</tbody>
</table>

Table 3   Distribution of the Time-Frequency Range of Sound Characteristics (%) and Time Intervals (ms) in Evolutionary Spectral Analysis
bone. However, the positioning of the microphones 1 cm in front of the tragus makes it hard to determine the change in the power of the sound and also the average energy of the entire signal. This is probably because the signal deformations originated from environmental noises during the record, although records were taken in a soundproof room.6,36

In related studies, many physiologic sites were selected for placement of the detector. It has been reported that when an accelerometer (microphone) is attached to the skin, a contact resonance resulting from its weight and the extensibility of the skin works as a low-pass filter to cut off high frequencies.37 Therefore, higher mean amplitude values of the mentioned studies could be related to the physical characteristic of the tubal structure of the auditory meatus, which might be attributed to separation of the TMJ signal from the surrounding noise.6,36

A significant number of study results have pointed out that joints with interference pathologies had larger energy than those without internal derangement.10,17,38 The current results showed that the energy levels were in the range of 1 to 8.9 × 10^−5 J, which is in accordance with those of the previous studies.10,17,37 Hutta et al found that TMJ sounds of the patients with internal derangements had nearly 4 times more energy (11.1 J) than those of the healthy subjects.38 In another study performed by Olivieri et al, it was noted that the averages of the vibratory energy in the patients with TMD presented higher values when compared to those in the asymptomatic group.10 In the present study, the total amount of energy values showed a decrease after splint therapy. So, it could be stated that such therapy might be efficient in this respect. Similarly, Mazzetto et al also stated that the total amount of the vibration energy of the TMJ sounds showed significant improvement after use for 4 weeks of a repositioning splint.17

The use of an ARS is one of the most widely accepted methods of treatment for the signs and symptoms of TMD with internal derangement. The ARS takes effect by altering the mandibular position. In this manner, anteriorly displaced discs could be recaptured, and so the new condyle-disc relationship could be stabilized.39 Although the primary goal of the use of an ARS is the reestablishment of a normal condyle-disc relationship, the treatment effect is generally provided with the morphologic alterations and remodeling of the joint structures over time (disc, ligament, and retrodiscal tissues) by diminishing the physical obstruction of the condyle translation. According to the results of the present spectral analysis, with the decrease in the mean amplitude, energy, and frequency values, treatment efficiency of ARS has been categorized as successful in 37% (7 of 19 patients) of the right joints and 44% (11 of 26 patients) of the left joints. Although the joint sounds were not completely eliminated in all patients, the intensity of the sounds was reduced. These results are also in agreement with the results of the study by Conti et al.23 This could be explained by the prevention of adverse loading of TMJ and progressive adaptation capabilities of TMJ structures, which could lead to improvement of joint sounds. Based on these results, it could be stated that the use of an ARS for a longer time might provide a further decrease in the TMJ sounds because of a longer adaptation time.

There have been many studies suggesting that ARS is effective for treating TMJ sounds in patients with internal derangements23,24,40; however, they are mostly based on clinical assessments.41 In fact, the best assessment method in evaluation of treatment efficacy of ARS on TMJ sounds is combining clinical evaluation with magnetic resonance imaging (MRI), as suggested previously.42 However, MRI is expensive and requires special equipment. Therefore, alternatively, electronic recording of joint sounds can be a useful tool in the evaluation of a treatment that is noninvasive, inexpensive, easily obtainable, and an objective and sensitive assessment method. Furthermore, the differences in sound frequency that cannot be detected by the human ear can be perceived by the electronic recordings. It does not require technical skill, and also does not lead to radiation exposure.

CONCLUSIONS

The results of the current study indicate that although ARS therapy had no effect on complete elimination of TMJ sounds, it influenced the types of sounds and other recorded parameters. Because the intensity of TMJ sounds decreased with ARS therapy for 6 weeks, the use of ARS for a longer period is a suggested topic for future studies. TMJ sounds could be objectively analyzed with electronic recordings.

ACKNOWLEDGMENTS

This research received no grant from any funding source. All procedures involving human participants performed in this study were in accordance with the ethical standards of the institutional committee and with the Helsinki Declaration. This study was approved by the ethics committee of the Faculty of Dentistry, Ankara University (Process no: 36290600/16-2013). No potential conflict of interest was reported by the authors.

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