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J DENT RES 1993 72: 871
DOI: 10.1177/00220345930720050701

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>> Version of Record - May 1, 1993
What is This?
Power Spectral Analysis of Temporomandibular Joint Sounds in Asymptomatic Subjects

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Very little has been done to quantify temporomandibular joint (TMJ) sound amplitudes and background noise and to determine the spectrum from healthy TMJs. Thus, the aim of this study was to record acoustically the sounds emitted by healthy TMJs with and without mandibular movements, for determination of baseline spectra. TMJ sounds were recorded bilaterally from 40 subjects with healthy joints by means of a self-developed recording system using miniature capacitor microphones inserted into the earpieces of a medical stethoscope placed in the meatus of the auditory canal. The recordings were performed without mandibular movements and during three consecutive opening and closing movements. The signals were high-pass-filtered at 50 Hz, low-pass-filtered at 2 kHz, and analyzed by fast Fourier transform computation on a 1024-point window (f_s = 5 kHz). The linearly weighted average baseline spectrum recorded without movement showed maximum values of 31 dB_SPL (sound pressure level) with a standard error of +2 to -3 dB. The linearly weighted average movement spectrum had a peak of 66 dB_SPL at 156 Hz and decreased almost linearly by about 40 dB/decade to 25 dB_SPL at 2000 Hz with a standard error of ±2 dB. Thus, the TMJ sound spectrum of mandibular movements in asymptomatic subjects differed at low frequencies by up to 35 dB from the baseline spectrum in absence of motion.


Introduction.

Temporomandibular joint (TMJ) sounds are considered a sign of structural or functional abnormalities of the joint, i.e., disc displacement or osteoarthrosis (Hansson and Nilner, 1975; Kopp, 1977; Farrar, 1978; Messenger and Barghi, 1987; Ciancaglini et al., 1987a; Bezuur et al., 1988; Greene and Laskin, 1988; Wanman and Agerberg, 1990). Several qualitative or semi-quantitative classification methods have been suggested for classification of TMJ sounds (Watt, 1980; Watt and McPhee, 1983; Oster et al., 1984; Eriksson et al., 1985; Gale and Gross, 1985; Morse et al., 1992), and electro-acoustical systems for recording and characterizing the sounds objectively have been introduced (Findlay and Kilpatrick, 1960; Ouellette, 1974; Widmalm and Larsson, 1981; Drum and Litt, 1985; Heffez and Blaustein, 1986; Ciancaglini et al., 1987b; Gay and Bertolami, 1987a; Toolson and Sadowski, 1991). Furthermore, several authors have associated different power spectra with various pathologies (Ciancaglini et al., 1987b; Gay et al., 1987). However, despite all these attempts to quantify, qualify, and use joint sounds for diagnosis of joint pathologies, only one paper analyzed the sound emitted by healthy joints (Gay and Bertolami, 1988). As pointed out by Widmer (1989), very little effort has been devoted to the quantification of sound amplitudes and baseline noise in the absence of motion.

The aim of this study was therefore to record TMJ sounds at rest and during jaw movement and to determine their power-frequency spectrum in a group of subjects with healthy TMJs.

Materials and methods.

Subjects.—Forty subjects (17 females and 23 males), aged 18-46 years (mean age of 26 years), without a past or present history of signs and symptoms of myoarthropathies of the masticatory system (MAP)—i.e., of craniomandibular disorders—were selected from the staff and students. To exclude a MAP, each subject had first to fill out a questionnaire. All individuals with a negative history were thereafter examined clinically according to the department's protocol (Palla, 1986). The examination included the auscultation of the TMJs with a stethoscope, the lateral and intrameatal palpation of the TMJs, the palpation of the masticatory and neck/shoulder muscles, and measurement of the unassisted mandibular mobility. The masticatory muscles examined were the temporalis muscle with its insertion, the masseter (deep and superficial), and the mandibular insertion of the medial pterygoid muscle. Pressure palpation was not calibrated. Tenderness to palpation was considered positive when it elicited a palpebral reflex or if the subject stated that it produced pain or discomfort. Symmetry of movements was checked visually by means of a ruler held in the mid-sagittal plane in front of the patient. This was also used for measurement of the movement capacity of the mandible, which had to be larger than 40 mm on opening and larger than 7 mm on protrusion and laterotrusion (Helkimo, 1974). Only subjects free of joint sounds, of TMJ and masticatory muscle tenderness, of pain on unassisted mandibular movements, and of deflections/deviations of the mandible on opening and protrusion of more than 2 mm were included in the study. Informed consent was obtained from all the subjects.

Experimental recording technique.—TMJ sounds were recorded simultaneously from both joints by means of two miniature capacitor microphones (Beyer MCE 5, Eugen Beyer Elektrotechnische Fabrik GmbH & Co., D-7100 Heilbronn, Germany) with a perfectly linear response between 20 and 2000 Hz. The microphones (diameter, 7 mm; length, 23 mm) were mounted in the earpieces of a medical stethoscope. The sound signals were pre-processed by dedicated hardware consisting of electronic amplifiers and filters. A sampling frequency of 5 kHz for each sound channel was chosen. A high-pass filter with a
cut-off frequency of 50 Hz and a slope of 60 dB/decade was used in order to suppress artifacts due to respiration and blood flow which, at our preliminary analysis, showed frequency contents of up to 45 Hz. Suppression of noise due to friction as well as anti-aliasing were achieved by use of a low-pass filter with 2 kHz cut-off frequency and a slope of -80 dB/decade.

The signals were stored by means of a self-developed system. This consisted of a 386 IBM-compatible personal computer and an analog-to-digital conversion board (DT2801-A, Data Translation Inc., Marlboro, MA). Software was developed to optimize the speed of this data conversion hardware and to record the data directly to disk, by means of the direct memory access (DMA) feature of the board. Sounds were recorded in a cyclic buffer of the computer RAM in which the last 3.3 s of the left and right signals were continuously stored. A play-back feature using the digital-analog conversion feature of the digitizing board was also implemented. This allowed the recorded signals to be played back on loudspeakers before analysis for detection of whether the recordings were contaminated with background or other spurious, extraneous noises. For the same purpose, the signals of both channels were also displayed graphically as time functions on the computer screen. These check-procedures were important, since recordings were performed in a non-anechoic room. The complete recording system was calibrated in sound pressure level (dB$_{SPL}$) in a free sound pressure field (Beranek, 1954). The sound pressure level in decibels is 20 times the logarithm to base 10 of the ratio between the measured effective sound pressure and the reference sound pressure of 20 μN/m$^2$ (Beranek, 1954).

The calibration was done by generation of pure sounds at known frequencies throughout the whole frequency band considered and at a known sound pressure level. A frequency-dependent conversion factor was then determined. The system noise, measured by short-circuiting of the microphone inputs, was around 15 dB$_{SPL}$ throughout the whole frequency band considered.

For frequency analysis, a time window of 205 ms was positioned around the maximum amplitude of the sound signal recorded during opening and closing. With a flat signal, the window was placed in the middle of the cycle. For spectra without mandibular movement, the window was placed in the middle of the whole recording. The analysis was performed by means of a Fast Fourier Transform (FFT) computation on a 1024-point window corresponding to a time interval of 205 ms. Only amplitude information was processed, and no phase relationship among components was considered. The power spectral density functions had a frequency range from 4.88 to 2500 Hz and a resolution of 4.88 Hz. However, frequencies below 50 Hz and above 2000 Hz were discarded because of the bandpass filtering applied to the signal. The amplitude of the frequency components was expressed in sound pressure level (dB$_{SPL}$). The power spectrum was linearly weighted; this means that it was not corrected in order to consider the reduced ear sensitivity at frequencies below 500 Hz and especially below 200 Hz.

Clinical procedure.—For the recordings, the subject sat in an office chair in a non-anechoic room. Care was taken to minimize environmental noise and speech. TMJ sounds were registered with the medical stethoscope inserted in the meatus of the auditory canal under two conditions. In a first series, they were recorded during 3.3 s without mandibular movements in order to determine the baseline signal. In the second series, the subject had to perform three maximum opening and closing movements without stopping, which had to start and end in maximum intercuspation. The opening and closing cycles were performed at a 1-Hz pace. This pace was displayed to the subject by means of a colored bar moving up and down on the computer screen. Before recording, the subjects were trained to open and close at the given pace with the recording apparatus in place. After each recording, the signals were examined visually on the computer screen and played back on loudspeakers to exclude the presence of spurious sounds. When signal contamination occurred, recordings were repeated.

Data analysis.—The frequencies at which 10, 25, 50, 75, and 90% of the total power occurred ($F_{10}$, $F_{25}$, $F_{50}$, $F_{75}$, and $F_{90}$) as well as the bandwidths between 10 and 90 and between 25 and 75% of the total power ($B_{10-90}$ and $B_{25-75}$) were calculated in order to characterize the shape of the power spectra and to analyze whether the shapes of the group-average spectra differed with statistical significance between the two sides, the recording with and without jaw movements as well as the opening and closing. The baseline spectra were analyzed for statistical differences by means of the Wilcoxon signed-ranks test, because the data were not normally distributed. For the analysis of the movement spectra, a one-way analysis of variance for repeated measures was used (Jennrich et al., 1990). Because of the skewed distribution, the data had to be logarithmically transformed. A significance level of p < 0.05 was chosen.

Results.

Baseline spectra.—The mean frequencies and standard errors at 10, 25, 50, 75, and 90% of the cumulative power as well as the bandwidths $B_{10-90}$ and $B_{25-75}$ of the baseline spectra of the left and right TMJ did not differ with statistical significance between the left and right sides (Wilcoxon signed-ranks test, p > 0.05) (Table 1). Therefore, for determination of the system's average baseline spectrum, the spectra of the left and right sides were

| TABLE 1 |
| Mean (± S.E.) of the Frequencies in Hz at 10, 25, 50, 75, and 90% and of the Bandwidths $B_{10-90}$ and $B_{25-75}$ of the Baseline Power Spectra of Asymptomatic TMJs |
| --- | --- | --- | --- |
| left | right |
| $F_{10}$ | 190.67 ± 9.03 | 179.93 ± 10.11 |
| $F_{25}$ | 293.46 ± 20.47 | 263.31 ± 20.20 |
| $F_{50}$ | 537.84 ± 41.05 | 462.16 ± 37.16 |
| $F_{75}$ | 857.67 ± 60.64 | 843.51 ± 55.36 |
| $F_{90}$ | 1343.75 ± 57.28 | 1287.47 ± 55.75 |
| $B_{10-90}$ | 1153.08 ± 53.32 | 1107.54 ± 50.10 |
| $B_{25-75}$ | 564.21 ± 54.78 | 580.20 ± 42.43 |
pooled. The linearly-weighted average baseline spectrum oscillated between 20 and 30 dB_{sPL}, with a weak pronounced peak of 31 dB_{sPL} at 771 Hz and a standard error of mainly +2 dB and -3 dB (Fig.). The asymmetry in the standard error is due to the logarithmic nature of the unit decibel. The audibility threshold in the Fig. is reminiscent of the decreasing sensitivity of the human ear at lower frequencies. The baseline spectrum was roughly 10 dB above the system noise (approximately 15 dB_{sPL}).

**Movements spectra.**—The power spectra recorded during movements did not differ with statistical significance either between sides or between opening and closing, as demonstrated by comparison at the frequencies at 10, 25, 50, 75, and 90% of the cumulative power as well as the bandwidths B_{10-90} and B_{25-75} (analysis of variance, p > 0.05) (Table 2). Therefore, all power spectra (left/right and opening/closing) were pooled. The linearly-weighted average spectrum in the presence of mandibular motion is shown in the Fig. It had a peak of 66 dB_{sPL} at 156 Hz and decreased almost linearly in parallel to the threshold of audibility by about 40 dB/decade to 25 dB_{sPL} at 2000 Hz with a S.E. of roughly ±2 dB. Therefore, the lower frequency bands (i.e., frequencies below approximately 750 Hz) had a greater representation than the higher ones with regard to the baseline spectrum in the absence of motion.

The linearly-weighted average spectrum recorded during jaw movements differed by up to 35 dB at lower frequencies from the baseline spectrum, whereas at higher frequencies the difference was less than 10 dB (Fig.). The mean frequencies at 10, 25, 50, 75, and 90% of the cumulative power as well as the bandwidths B_{10-90} and B_{25-75} of the baseline and movements spectra differed with statistical significance (Wilcoxon signed-ranks test, p > 0.05).

**Discussion.**

Our system showed a fairly constant baseline spectrum, which differed significantly from that recorded during jaw movements at frequencies below 800 Hz. The movement spectrum obtained was comparable with the smoothed spectral envelope for normal TMJ sounds reported by Gay and Bertolami (1988). However, since they reported the results in relative amplitudes, the results can be compared only in the frequency but not in the amplitude domain. The power spectrum of healthy TMJs is different from that of other healthy joints, e.g., knee joints, for which two maxima—the first one around 200 Hz and the second one in the 1-kHz region—are found (Chu et al., 1978). These differences can most likely be explained by the differences in anatomy, dimensions, and biomechanics of the joints as well as by those in the recording systems.

The movements spectra showed a peak of 66 dB_{sPL} at 156 Hz. These frequencies can hardly be heard by the patient or by the clinician because of the reduced sensitivity of the human ear in this frequency range (Beranek, 1954). The threshold of audibility subtracts approximately 30 dB at the peak frequencies and brings the oscillations to a low acoustical perception level. Indeed, the acoustical equal-loudness contours of the human ear show, for instance, that a 50-Hz tone of 50 dB_{sPL} is perceived at the

**TABLE 2**

| AND OF THE BANDWIDTHS B_{10-90} AND B_{25-75} OF THE MOVEMENT POWER SPECTRA OF ASYMPTOMATIC TMJs |
|--------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| F_{10} | 163.58 ± 6.15 | 166.54 ± 5.96 | 163.78 ± 6.74 | 168.66 ± 6.01 |
| F_{25} | 244.43 ± 12.23 | 242.35 ± 11.32 | 252.60 ± 18.55 | 245.93 ± 10.95 |
| F_{50} | 454.71 ± 30.88 | 422.12 ± 24.23 | 443.68 ± 29.60 | 417.93 ± 22.14 |
| F_{75} | 716.31 ± 44.54 | 764.32 ± 43.06 | 707.03 ± 44.10 | 754.11 ± 41.30 |
| F_{90} | 1037.31 ± 54.07 | 1138.63 ± 50.30 | 1038.86 ± 51.87 | 1095.99 ± 51.22 |
| B_{10-90} | 873.74 ± 49.36 | 972.09 ± 46.46 | 875.08 ± 47.01 | 927.33 ± 46.97 |
| B_{25-75} | 471.88 ± 37.58 | 521.97 ± 35.51 | 454.43 ± 36.04 | 508.18 ± 34.19 |
TABLE 3
MEAN (+ S.E.) OF THE FREQUENCIES IN Hz
AT 10, 25, 50, 75, AND 90% AND OF THE BANDWIDTHS B_{10:90} AND B_{25:75} OF THE BASELINE POWER SPECTRA OF THE LEFT AND RIGHT TMJs
AND OF THE MOVEMENT SPECTRA OF THE LEFT AND RIGHT TMJs

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_{10}</td>
<td>185.30 ± 9.56</td>
<td>165.64 ± 3.10</td>
</tr>
<tr>
<td>F_{25}</td>
<td>278.38 ± 20.34</td>
<td>246.33 ± 6.79</td>
</tr>
<tr>
<td>F_{50}</td>
<td>500.00 ± 39.38</td>
<td>434.61 ± 13.45</td>
</tr>
<tr>
<td>F_{75}</td>
<td>850.56 ± 57.70</td>
<td>755.44 ± 21.56</td>
</tr>
<tr>
<td>F_{90}</td>
<td>1315.61 ± 56.33</td>
<td>1077.70 ± 25.93</td>
</tr>
<tr>
<td>B_{10:90}</td>
<td>1130.31 ± 52.53</td>
<td>912.06 ± 23.73</td>
</tr>
<tr>
<td>B_{25:75}</td>
<td>572.21 ± 48.70</td>
<td>489.12 ± 17.91</td>
</tr>
</tbody>
</table>

same loudness level as a 1-kHz tone of 20 dB_{re} (Zwicker and Fastl, 1990). The lower frequencies caused by respiration and blood flow, which were detected in the preliminary analysis, are therefore hardly perceptible to the human ear.

For the comparison of the spectra of healthy and diseased joints, it may be important to represent the spectra in absolute units instead of relative amplitude as reported by Gay and Bertolami (1988). Indeed, the representation of a low-amplitude spectrum in relative units can erroneously emphasize irrelevant maxima, giving the impression that they are significant, thus limiting the possibility of comparing the spectra of normal and pathological TMJs. The power spectra of healthy and diseased knee joints recorded during movements differed in amplitude, which was directly correlated to the severity of the cartilage damage (Chu et al., 1978). Therefore, for quantitative comparison of spectra of sounds from different joints, the system was calibrated in a free sound pressure field. This was also important because the recording system appeared to emphasize more the lower than the higher frequencies, although the microphones had a perfectly linear response in the recorded frequency range. This phenomenon was possibly due to the acoustical transfer function of the stethoscope earpieces into which the microphones were inserted. However, it was not responsible for the maximum around 156 Hz found in the movement spectrum. This peak was probably due to the microphone positioning. In fact, although this placement allowed for an easy and reproducible set-up without the need for any contact gel or reference marks, it also produced a mechanical occlusion effect of the ear canal which emphasizes low frequencies (Howell et al., 1988). This microphone position was chosen after several positional tests. With the present recording system, this location maximized the amplitude of the recorded signals while minimizing movement artifacts. Okazaki (1989) reported that clear and stable TMJ sounds could be recorded from the external auditory meatus. Healthy TMJs produced sounds which were distinctly different from baseline and background noise at lower frequencies. Normative data, as are those we collected, are relevant for a systematic study of TMJ sounds. The small standard error found in the average spectrum, even with different subject morphologies, is encouraging for continuing the TMJ sound research with absolute acoustic level. However, this recording technique remains experimental, because it requires constant control and calibration of the recording system for proper data acquisition to be ensured.

Acknowledgments.
We thank Drs. G. Lavigne and C. Stohler for reading the manuscript and for their suggestions.

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