

## Acoustic characteristics of sounds from temporomandibular joints with and without effusion: an MRI study

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**SUMMARY** Joint effusion has been associated with temporomandibular joint (TMJ) pain but can only be diagnosed by magnetic resonance imaging (MRI). For screening of patients with suspected effusion a simple and less expensive method would be desirable. We recorded joint sounds during jaw opening and closing movement from 34 TMJs with internal derangement (ID). Seventeen joints had joint effusion seen on MRI. Spectrograms of the sounds were displayed as waterfall plots showing profiles of the

consecutive Hamming windows. If the profiles were similar, as judged by initial evaluation, the displayed pattern was classified as stable. If some profiles were distinctly deviating in their pattern, this was classified as unstable. Joints with effusion showed unstable sound pattern more often than joints without effusion ( $P < 0.001$ ). It was concluded that TMJ sound analyses have a potential to identify joints with effusion based on their unstable sound pattern.

### Introduction

Joint effusion may occur in joints with inflammatory arthritis (Takahashi *et al.*, 1999). One characteristic sign is capsular pattern of restriction because of the distension of the joint capsule by extensive intra-articular synovial fluid. Portions of the capsule that are normally lax allowing freedom of movement may become taught because of the capsular distension causing changes in joint kinematics (Hertling & Kessler, 1996).

Temporomandibular joint (TMJ) effusion is associated with pain (Westesson & Brooks, 1992). In patients with joint dysfunction it is desirable to diagnose the cause of the pain because such knowledge helps in deciding how to manage the treatment (Hertling & Kessler, 1996). However, unless there is a large collection of fluid in the TMJ or an invasive procedure is used, effusion can only be diagnosed by magnetic resonance imaging (MRI) (Schellhas & Wilkes, 1989), which is expensive and often not available or affordable. There is therefore a need for a simpler and less

expensive method for screening patients with TMJ pain for possible effusion.

There is still no general agreement about the prevalence and natural course of TM disorders (TMD). One reason is the lack of simple non-expensive, non-invasive methods that can be used in mass examination of a population. Nor is there any method that can be used alone to make a diagnosis. Multi-phasic screening with simultaneous use of multiple laboratory and clinical procedures for the detection of the various diseases or pathologic conditions is needed. Analysis of electronically recorded TMJ sounds is a procedure that has the potential to be of value when used in combination with other diagnostic tools. Sound recording, like most other diagnostic tools, should not be used alone as basis for the diagnosis of any TMD. It has, however, a potential value in screening by helping to identify risk groups.

The TMJ sounds are often noticed in joints with internal derangement (Widmalm *et al.*, 1992; Ishigaki *et al.*, 1992, 1994) that is a dominant characteristic of

joints with effusion (Westesson & Brooks, 1992). Joint effusion can be expected to change the mechanical properties of the intracapsular tissues. Because TMJ sound is a mechanical phenomenon (Widmalm *et al.*, 1992) changes in the acoustic characteristics of TMJ sounds may be associated with joint effusion.

The aim of this study was to test the null hypothesis that there are no visually observable differences in the time frequency distributions of sounds from joints with and joints without effusion as diagnosed on T2-weighted MR images.

## Subjects

The group consisted of 24 patients, mean age 29.9 years, age range 19–56, 19 females and five males, who had been referred for MRI examination because of suspected TMJ internal derangement (ID). Seventeen patients were clinically diagnosed as having bilateral ID. Four patients were found to be normal without signs of pathology observable on MR images. Their joints were not included in the study, which thus was based on findings in 34 joints with ID.

## Methods

The MRI was performed with a Siemens 1.0 Tesla MR imager (Magnetom impact)\* using surface coils of a type designed for TMJ imaging. Corrected sagittal images were obtained in the closed- and open mouth positions using fast spin echo technique. The scan parameters are listed in Table 1. On T2-weighted images, joint effusion was identified as an area with homogeneous and high signal intensity in the joint space (Westesson & Brooks, 1992).

On the basis of the imaging findings, the 34 joints with ID characterized as described in a previous study (Sano & Westesson, 1995) were divided into three subgroups (Table 2). Seventeen joints with ID were found to have effusion in the joint space as observed on the sagittal T2 images. Seventeen joints had ID but without effusion. The 17 joints with derangement but no effusion served as controls when comparing sound characteristics between joints with and joints without effusion. The joints were also classified according to the type of displacement. Twenty joints had disc displacement with reduction (DDR) and 14 joints had perma-

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**Table 1.** Magnetic resonance imaging parameters

Scan parameters	Axial	Sagittal closed-mouth	Sagittal open-mouth
Time of repetition (ms)	200	2080	2080
Time of echo (ms)	15	17/85	17/85
No. of signal averages	1	3	2
Field of view (cm)	30	12	12
Slice thickness (mm)	5	3	3
Matrix	256 × 256	256 × 256	256 × 256
Scan time (s)	54	317	213

**Table 2.** Distribution and status of joints with internal derangement

	Joint effusion	No joint effusion	Sums in rows
DDR	10	10	20
DD	6	6	12
DJD and DD	1	1	2
Sums in columns	17	17	34

Distribution and status of 34 joints with internal derangement from 17 patients. DDR, disc displacement with reduction; DD, disc displacement without reduction; DJD, degenerative joint disease.

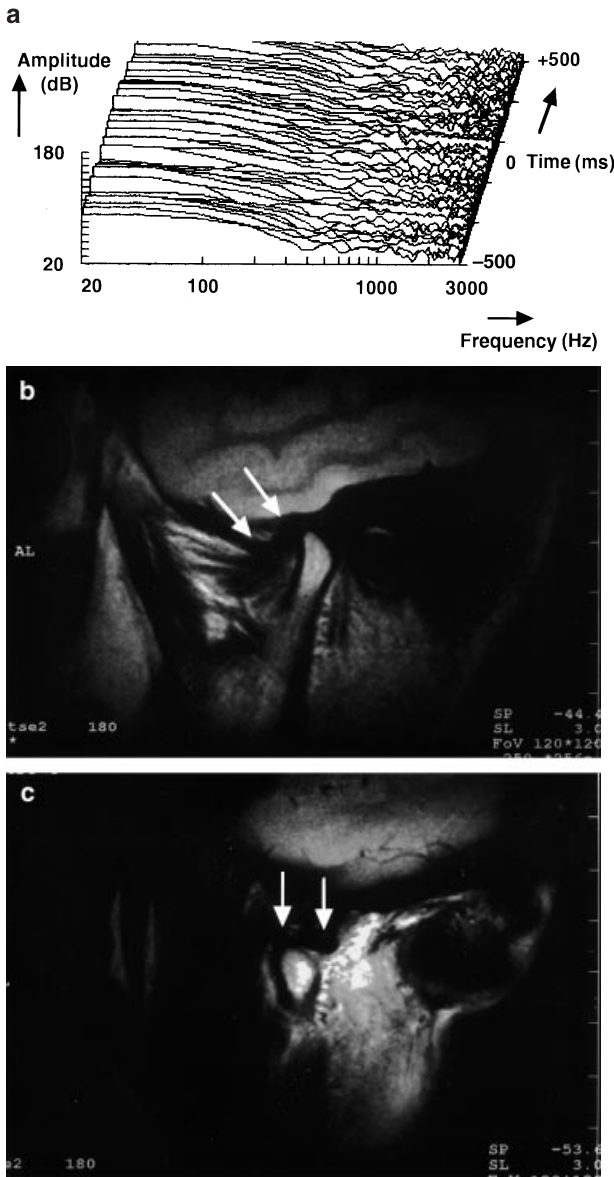
nent disk displacement (DD). Two of the joints with DD had also degenerative joint disease (DJD). The number of joints with ID was too small to analyse for possible differences in sound characteristics because of differences in the type of displacement or degenerative changes. Future studies on larger groups will take those parameters into consideration.

The TMJ sounds were bilaterally recorded using two electret condenser microphones placed at the auditory meati and fastened in a stable position using Colto Flex Putty. The sound signals were recorded with a Digital Audio Tape (DAT) recorder<sup>†</sup> and sampled with a rate of 48 kHz.

Recordings for analysis were made during three consecutive jaw opening–closing movements. The time duration of each opening–closing cycle was about 3 s. The patient opened, paused for about 1 s and closed guided by lights being turned on and off on a ‘silent metronome’ (Dr Beat DB-66)<sup>‡</sup>. The signals from the metronome were recorded on separate channels and used to identify the borders between cycles and the opening versus closing phases in each cycle.

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**Fig. 1.** The time–frequency distribution with a stable pattern from a TMJ sound recording made during the opening phase (a) and sagittal T2-weighted images (2080/85) (b, c) from a 24-year-old woman. The T2-weighted images showed TMJ with disc displacement with reduction without joint effusion. On closed-mouth image (b), the disc (white arrows) was located anterior to the condyle. On open-mouth image (c), the disc (white arrows) was between the condyle and the tubercle of the temporal bone. Joint effusion was not seen in the upper, nor in the lower joint space.

The sound recordings were first displayed in their analogue form. From each opening and closing phase of the three cycles per patient a segment of 1000 ms duration, including the entire opening or closing

movement, was chosen for time–frequency analysis. Thereby sounds, if occurring, were sure to be included in the segments. Thus 204 sample recordings were obtained from 34 joints for spectral analysis.

The time–frequency distribution of each segment was displayed using the short time fast Fourier transform (STFT) to calculate power spectra of 50 consecutive Hamming windows. Each window had a time length of 20 ms and the frequency range was 20–3000 Hz. This type of display produces what is commonly known as a waterfall plot (Steiglitz, 1996). It gives the illusion of a three-dimensional plot, with distance from the time–frequency plane representing frequency content. If the 50 profiles in this ‘waterfall’ were similar as judged by visual evaluation, the displayed pattern was classified as stable (Fig. 1a). If some profiles showed distinctly deviating profiles the pattern was classified as unstable (Fig. 2a). If the pattern was close to stable but with deviations too small for classifying as unstable, the pattern was designated indeterminate.

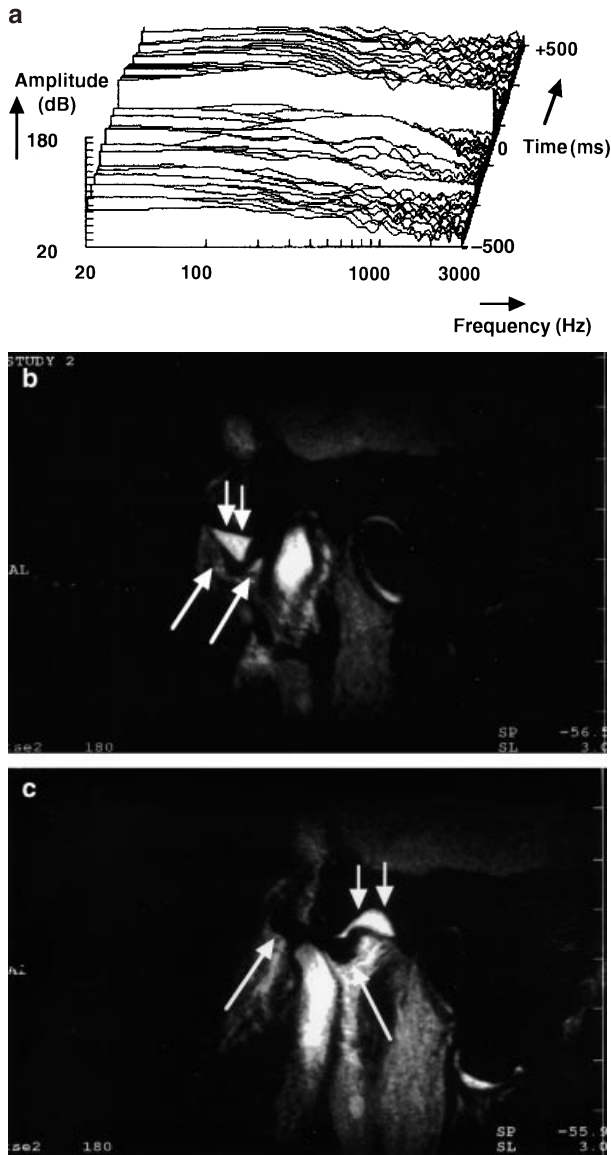
The time–frequency distribution patterns were independently evaluated and classified as stable, unstable or indeterminate by two of the authors (TS and MY). The graphs were presented for evaluation in random order.

*Statistical analysis*

Two-sided Wilcoxon’s rank sum test was used to compare the distribution of samples with joint effusion with those without joint effusion. Differences in stability of sound patterns between the two groups were analysed using the two-sided Wilcoxon’s rank sum test. An  $\alpha$ -level of 0.1% was chosen.

**Results**

The time–frequency distributions of sounds from TMJs with joint effusion showed unstable pattern more often than the sounds from joints without effusion ( $P < 0.001$ ). The results are summarized in Table 3. Of the 102 samples from the 17 joints with effusion 29.4% showed stable (Fig. 1a) time–frequency distributions, 37.3% were unstable (Fig. 2a) and 33.3% were classified as indeterminate. Of the 102 samples from the 17 joints without effusion 52.9% were stable, 9.8% were unstable, and 37.3% were judged as indeterminate.



**Fig. 2.** Time–frequency distribution (a) with unstable pattern from TMJ sound recorded during the opening phase and sagittal T2-weighted images (2080/85) (b,c) from a 28-year-old man. The T2-weighted images (b, c) showed TMJ with disc displacement with reduction with joint effusion. On closed-mouth image (b), the disc (white arrows) was located anterior to the condyle. On open-mouth image (c), the disc (white arrows) was between the condyle and the tubercle of the temporal bone. Joint effusion (short arrows) was seen in the upper joint space. On open-mouth image (c), joint effusion (short arrows) was located posterior to the condyle.

**Discussion**

The result of this study, indicating that sounds from joints with ID and effusion differ from sounds from

**Table 3.** Distribution of time–frequency patterns (tfp)

	Unstable tfp	Indeterminate tfp	Stable tfp
17 joints with effusion	37.3% (38)	33.3% (34)	29.4% (30)
17 joints without effusion	9.8% (10)	37.3% (38)	52.9% (54)

Number of samples is given within parenthesis. The table shows the distribution of time–frequency patterns (tfp) from 204 sound recording samples from 34 TM joints, 17 joints with and 17 joints without joint effusion. The patterns were more stable in the group of joints without effusion ( $P < 0.001$ ) (two-sided Wilcoxon’s rank sum test).

joints with ID but no effusion, is of high clinical interest because a strong association has been reported between TMJ effusion and TMJ pain (Westesson & Brooks, 1992). Diagnosis of joint effusion, which therefore is valuable information for the clinician, can be obtained from MR images (Schellhas & Wilkes, 1989). For screening patients with TMJ pain and suspected joint effusion, a simpler and less expensive method would be desirable. No studies on the acoustic characteristics of TMJ sounds associated with joint effusion have so far been reported. In this study, we tested the relationship between acoustic characteristics of TMJ sounds and evidence of joint effusion using a previously published method (Yoshida *et al.*, 1994) for detecting TMJ sounds and for analysis of the time–frequency distribution of sounds.

The results indicate that analysis of differences in acoustic characteristics could make it possible to objectively diagnose joint effusion. The reason for why the sounds may be different is most probably that inflammatory processes connected with effusion change the mechanical properties of the intra capsular elements and thereby the acoustic characteristics of the TMJ sound which is a mechanical phenomenon (Widmalm *et al.*, 1992).

The methods for signal analysis differ between authors. Power spectra have been used for sound/vibration signal analysis in a number of well-documented studies (Ishigaki *et al.*, 1993; Tallents *et al.*, 1993; Ishigaki *et al.*, 1994). Those methods do, however, not reveal how the frequency content changes in time. This means that for the human ear very different sounds can have power spectra that are exactly the same.

One method to overcome the limitations of power spectra and give a representation of how the signal frequency content varies in time is to perform the STFT on small consecutive segments (windows) of the signal and display its magnitude as power spectra of each window along a time axis (Kimoto *et al.*, 1996; Sano *et al.*, 1999). This type of time–frequency spectral analysis is often referred to as the ‘sliding window’ technique. The plot of spectra from a number of such consecutive windows is usually called a waterfall plot (Steiglitz, 1996). Such a method was also used in this study. A 1000-ms segment was divided into 50 consecutive segments (Hamming windows) of 20 ms duration and the resulting power spectra were displayed along a time axis as illustrated in Figs 1a and 2a. An advantage with this method is that it is simple to use and there are several not too expensive programs commercially available. It does give a fair idea of how the frequency content varies in time. Each window is represented in the plot by its power spectrum, which is produced using a filtering process. Ideally the spectrum for each window should represent only that particular window’s content. In practice, however, signal components from the parts of the sound before and after a window will always to some extent ‘contaminate’ its spectrum. Using a special type of filter can minimize that error. We choose the Hamming filter (Balmer, 1991) but it is beyond the scope of this paper to describe the pros and cons with different filters. The reader is referred to the discussions in literature about digital signal processing such as Balmer (1991) and Lyons (1997).

The disadvantage with the ‘sliding window’ method is that there is a tradeoff between resolution in time and resolution in frequency (Widmalm *et al.*, 1991; Williams, 1996). The higher the resolution is in time, the lower it is in frequency and vice versa. This is another example of the uncertainty principle often mentioned in physics explaining why position and velocity of an atomic particle cannot be measured accurately at the same time. In our application it means that if we want a precise measurement of the frequency content we need a large window where the variations in time are smoothed out and not very accurate. If we want precise information about how the signal varies in time we need small windows and loose information about the exact frequency content.

The uncertainty about the exact frequency content for every position in time in sound signal analysis is

now being overcome by applying a new method for time–frequency analysis (Widmalm *et al.*, 1991; Williams, 1996). The use of that type of time–frequency distribution, reduced interference distribution (RID) gives a more truthful representation of how the frequency content is distributed in time. It is, however, technically more difficult to apply with high demands on computer power. It cannot be as easily applied, as the ‘sliding window’ method, but future studies should consider using the RID.

Pain can occur in the TMJ area for many reasons. The outcome of treatment and the effect of pain relieving medication are naturally significantly dependent on a correct differential diagnosis. This is, however, a major challenge in TMD clinics. In conclusion TMJ sound analyses have the potential to identify joints with effusion based on their unstable sound pattern. Further studies on larger samples with more advanced methods for displaying the time–frequency distributions of the sounds and studies where the effect on the sound characteristics by different types of ID can be considered are, however, needed for a confirmation of these preliminary results.

## References

- BALMER, L. (1991) *Signals and Systems*, pp. 373, 2nd edn. Prentice Hall, London.
- HERTLING, D. & KESSLER, R.M. (1996) *Management of Common Musculoskeletal Disorders*, p. 34, 3rd edn. Lippincott-Raven Publishers, Philadelphia.
- ISHIGAKI, S., BESSETTE, R.W. & MARUYAMA, T. (1992) The distribution of internal derangement in patients with temporomandibular dysfunction- prevalence, diagnosis, and treatments. *Journal of Craniomandibular Practice*, **10**, 289.
- ISHIGAKI, S., BESSETTE, R.W. & MARUYAMA, T. (1993) Vibration analysis of the temporomandibular joints with degenerative joint disease. *Journal of Craniomandibular Practice*, **11**, 276.
- ISHIGAKI, S., BESSETTE, R.W. & MARUYAMA, T. (1994) Diagnostic accuracy of TMJ vibration analysis for internal derangement and/or degenerative joint disease. *Journal of Craniomandibular Practice*, **12**, 241.
- KIMOTO, K., AOKI, H., TAMAKI, K. & FUJIWARA, M. (1996) A three dimensional display for TMJ sounds using SFFT. *Bulletin of Kanagawa Dental College*, **24**, 19.
- LYONS, R.G. (1997) *Understanding Digital Signal Processing*, pp. 81, 407. Addison-Wesley, Reading, MA, USA.
- SANO, T. & WESTESSON, P.L. (1995) Magnetic resonance imaging of the temporomandibular joint: Increased T2 signal in the retrodiscal tissue of painful joints. *Oral Surgery Oral Medicine Oral Pathology*, **79**, 511.
- SANO, T., WIDMALM, S.E., WESTESSON, P.L., TAKAHASHI, K., YOSHIDA, H., MACHI, K. & OKANO, T. (1999) Amplitude and

- frequency spectrum of TMJ sounds from subjects with and without other TMD signs/symptoms. *Journal of Oral Rehabilitation*, **26**, 145.
- SCHELLHAS, K.P. & WILKES, C.H. (1989) Temporomandibular joint inflammation: comparison of MR fast scanning with T1- and T2-weighted imaging techniques. *AJR-American Journal of Roentgenology*, **153**, 93.
- STEIGLITZ, K. (1996) *A Digital Signal Processing Primer*, pp. 212. Addison-Wesley, Menlo Park, CA, USA.
- TAKAHASHI, T., NAGAI, H., SEKI, H. & FUKUDA, M. (1999) Relationship between joint effusion, joint pain, and protein levels in joint lavage fluid of patients with internal derangement and osteoarthritis of the temporomandibular joint. *Journal of Oral and Maxillofacial Surgery*, **57**, 1187.
- TALLENTS, R.H., HATALA, M., KATZBERG, R.W. & WESTESSON, P.L. (1993) Temporomandibular joint sounds in asymptomatic volunteers. *Journal of Prosthetic Dentistry*, **69**, 298.
- WESTESSON, P.L. & BROOKS, S.L. (1992) Temporomandibular joint: relationship between MR evidence of effusion and the presence of pain and disk displacement. *AJR-American Journal of Roentgenology*, **159**, 559.
- WIDMALM, S.E., WESTESSON, P.L., BROOKS, S.L., HATALA, M.P. & PAESANI, D. (1992) Temporomandibular joint sounds: correlation to joint structure in fresh autopsy specimens. *American Journal of Orthodontics and Dentofacial Orthopedics*, **101**, 60.
- WIDMALM, S.E., WILLIAMS, W.J. & ZHENG, C. (1991) Time frequency distributions of TMJ sounds. *Journal of Oral Rehabilitation*, **18**, 403.
- WILLIAMS, W.J. (1996) Reduced interference distributions: biological applications and interpretations. *Proceedings of the IEEE*, **84**, 1.
- YOSHIDA, H., SANO, T., KATAOKA, R., TAKAHASHI, K. & MICHII, K. (1994) A preliminary investigation of a method of detecting temporomandibular joint sounds. *Journal of Orofacial Pain*, **8**, 73.
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