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Vibrations in the human middle ear

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Summary

Background:

Middle ear surgery techniques can improve hearing destroyed by disease, but results of treatment are difficult to predict. Therefore, researchers use a Laser Doppler Vibrometer to measure vibrations of human middle ear ossicles.

Material/Methods:

Measurements of ossicular chain vibrations are performed on fresh human temporal bone specimens using Laser Doppler Vibrometer. Vibrations of stapes are recorded in 3 cases: 1) for intact ossicular chain, 2) when incus long process is removed, and 3) after long process reconstruction with bone cement. A typical analysis of transfer function is completed by other methods applied in dynamics.

Results:

Measurements and analysis of stapes vibrations in case of intact and damaged ossicular chain show regular and irregular behavior which can be recognize with the help of phase portraits, recurrence plots, correlation dimension, and Hurst and Lyapunov exponents. The long process reconstruction with bone cement gives good results in improving hearing.

Conclusions:

Recurrence plots, and Lyapunov and Hurst exponents used in the study complete information obtained from transfer function and can be employed to enrich the classical approach to ossicular chain vibrations.

key words:

middle ear vibrations • laser doppler vibrometer • nonlinear dynamics

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BACKGROUND

Middle ear surgery techniques can improve hearing destroyed by disease. Various procedures are currently used in clinical practice, ranging from relatively simple ossicles reconstruction to middle ear prostheses. Many factors, like variation in anatomy, Eustachian tube malfunction, healing or mucosal disease, have a significant impact on the final result. This is why many researchers use a Laser Doppler Vibrometer (LDV) as a tool to measure vibrations of human middle ear ossicles [1–3]. Results of measurements of ossicles vibrations are usually presented as the transfer function that is a relationship between input signal (usually a sound source) and output signal (displacement or velocity of middle ear ossicles). Middle ear prostheses are very popular in surgery practice, therefore an influence of prosthesis head size, prosthesis length, or material used over prosthesis is analyzed [4]. A separate problem is a prosthesis placement on different sites on the stapes footplate and its influence on velocity and displacement of the ossicles [5]. Another study presents an anatomically shaped incus prosthesis used for reconstruction of the ossicular chain [6]. In all the cited studies the transfer function is engaged as a measure of efficiency of ossicles chain reconstruction.

Many different prostheses are used in clinical practice, and estimation of their effectiveness plays a key role. Until now, medical specialists have generally made use of the transfer function as a factor that contains the information about the correctness of the applied method of treatment.

This paper proposes a new approach to observe vibrations of the middle ear ossicles and to compare the quality of vibration of the reconstructed ossicular chain with an intact one. Moreover, vibrations of ossicles are presented when incus long process is absent. The tools used in nonlinear mechanics, like phase portraits, recurrence plots (RP), and Hurst and Lyapunov exponent, are applied to recognize a vibration type.

MATERIAL AND METHODS

Sample preparation

Measurements of ossicular chain vibrations were performed on fresh human temporal bone specimens. Temporal bone samples were harvested within 48 hours after death and preserved in a solution of normal saline with 10 ml of 10% Betadine at 5°C between measurements. The soft tissue was removed and a standard antromastoidectomy with posterior tympanotomy was performed. The mastoid facial nerve was removed to visualize the stapes arch end footplate. The ear canal was drilled, leaving about 2–3 mm of bone around the tympanic annulus. An artificial external ear canal of 25 mm length and 9 mm diameter was then attached to the bone with epoxy resin. The artificial canal has 2 ports – one for a microphone (ER-7C Etymotic Research) and a second for a sound source (ER2 Etymotic Research) placed about 2 mm from the tympanic membrane. The artificial canal was closed with a glass plate to create a sound seal chamber. Pieces of a retroreflective tape (0.5 mm²) weighing less than 0.05 mg were placed on the footplate of the stapes. The temporal bone specimen was then embedded in dental cement and put in a temporal bone holder (Storz).

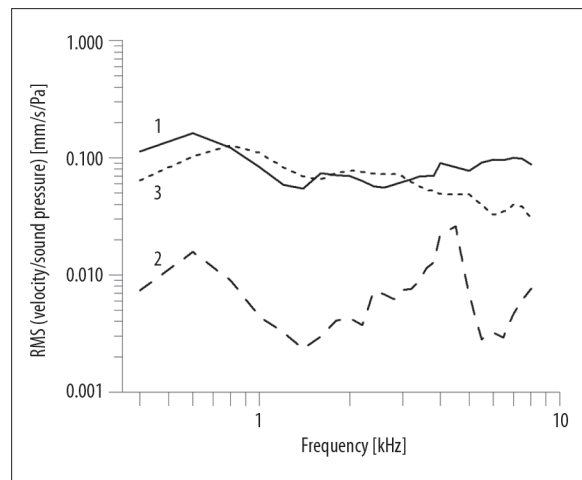


Figure 1. Stapes velocity normalized for ear canal sound pressure level in intact ossicular chain (1), long process of the incus absent (2), and incus rebuild with bone cement (3).

Measurements of stapes velocity and displacement in a temporal bone specimen were performed as follows. Firstly, vibrations of intact ossicular chain were measured, then the incus long process was removed and movement of the stapes was recorded. After that, the incus long process was rebuilt with bone cement to connect it to the stapes head. Then, measurements of footplate vibrations were repeated. The results were analyzed in classical manner as a transfer function and a comparison followed by additional analysis with phase portraits, recurrence plots, correlation dimension, and Hurst and Lyapunov exponent were conducted.

Experimental setup

The measurements were performed on an antivibration table inside a sound booth. Sound stimuli were frequency sweeps from 0.2 to 8 kHz at 80–110 dB sound pressure level (SPL). The sound source (ER2 Etymotic Research) was connected to a power amplifier to produce an adequate signal output. The stapes footplate velocity and displacement were measured with a Laser Doppler Vibrometer system composed of an OFV-5000 controller with a DD-500 displacement decoder and a VD-06 velocity decoder (Polytec). An OFV-534 sensor head was connected to a joystick-operated micromanipulator mounted on an operating microscope. A helium-neon laser beam was directed with the micromanipulator on retroreflective targets on the object of investigation through the artificial ear canal or posterior tympanotomy [7]. Additionally, sound pressure level (SPL) was measured by hear microphone (ER-7C Etymotic Research) in order to build the transfer function between the output (vibrations) and the input (SPL). The measurements were recorded using an NI6210 processing board (National Instrument) and DasyLab software and then the experimental data was analyzed with the MatLab package.

RESULTS

Classically, the outcomes of experiment are presented as the transfer function. In this study, the transfer function was also used in order to compare its results with other methods. The root mean square value (RMS) of the target's velocity was normalized to sound pressure level recorded simultaneously

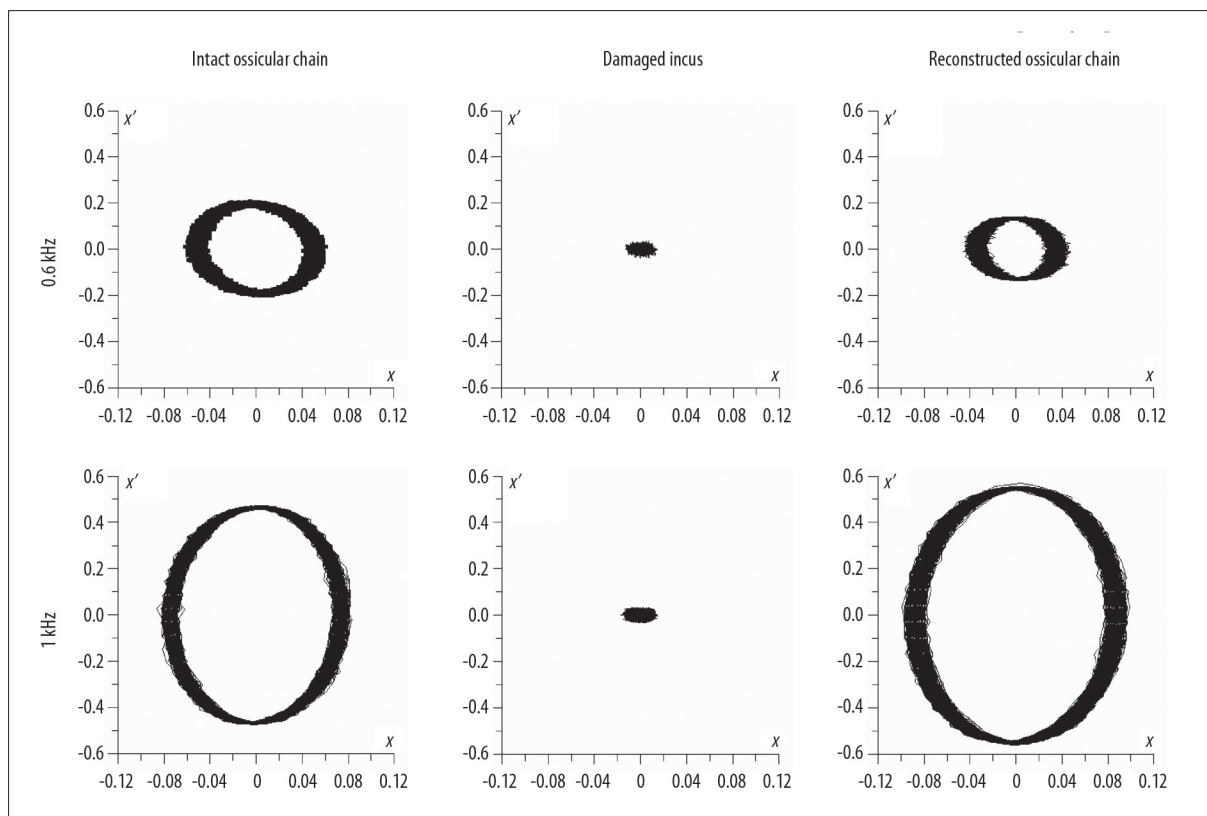


Figure 2. Phase portraits for 0.6kHz, 1kHz in case of intact ossicular chain, long process of the incus absent, incus rebuild with bone cement.

from the artificial external ear canal. The transfer function in case of intact ossicular chain (No.1), long process of the incus absent (No.2), and ossicular chain reconstructed with bone cement (No.3) is shown in Figure 1.

Naturally, the intact ossicular chain characterizes the best features, the level of vibrations velocity is the highest. The long process of the incus absent (No. 2) shows a similar course of transfer function but with smaller amplitudes. Reconstruction with bone cement is very efficient because vibrations characteristic in this case are almost the same as in the intact ear; however, there is a slight decrease of velocity for frequencies below 0.8 kHz, and over 3 kHz. Moreover, starting from 4 kHz the curves 1 and 3 become divergent, suggesting that the distribution of dominant frequencies can be changed quantitatively and qualitatively above 4 kHz, and can have an influence on proper signal recognition by a human being.

Additional information cannot be gained based only on transfer function. Therefore, there is reason to propose further analysis based on phase portraits (Figure 2), where x means displacement and x' – velocity. It turns out that vibrations at chosen frequencies of 0.6kHz and 1kHz have a periodic nature both for the intact ossicular chain and the reconstructed one, while in the case of incus damage the vibrations are stochastic-like. A phase portrait contains variable x and x' where x results from analogue integration of velocity (x'), therefore it is better to analyze only original signal x' then x . Recurrence plot (RP) technique should provide a deeper view of dynamics because to create RP only 1 coordinate (signal) is required.

Recurrence plots were originally based on Taken’s theorem [8]. According to this, the state of the system can be represented by the time delay vector:

$$X_i = [x_i, x_{i-\tau}, x_{i-2\tau}, \dots, x_{i-(m-1)\tau}] \quad (1)$$

where m means embedding dimension and τ – time delay. If a distance between x_i and x_j is less than a threshold, the recurrence between these points exists and such a state is represented by a dot in the recurrence plot. Looking at recurrence plots (Figure 3) drawn for typical frequencies 0.6 and 1 kHz, we observe regular motion, which is represented by long diagonal lines, in the case of intact ossicular chain and the reconstructed incus. Interestingly, regular motion exists also for damaged incus at stimulus of 1 kHz, while for 0.6 kHz motion can be stochastic and even chaotic. The reason for this lies in SPL because a stimuli signal is generated with the same amplitude that produces various auditory impressions measured by SPL.

One can conclude that even when the long process of incus is damaged, the stapes can vibrate regularly at some frequencies if the stimulus is strong enough.

The problem of irregularity, shown in Figure 3 for frequency of 0.6 kHz when incus long process is damaged, is still unsolved; therefore the theory of correlation dimension, Hurst’s and Lyapunov’s exponent is applied here. Grassberger and Procaccia [9] suggested that the correlation dimension is a good tool for distinguishing random from chaotic time series. A general rule of bigger correlation dimension (D_2) for long process of the incus absent (No. 2)

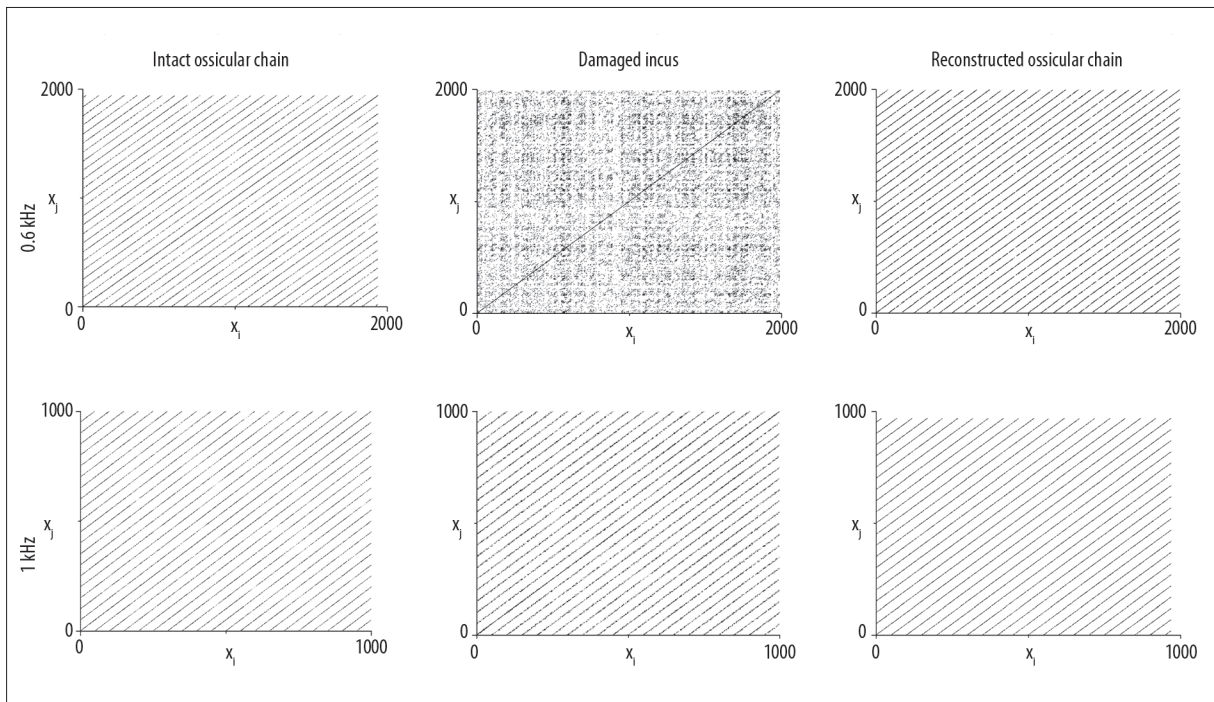


Figure 3. Recurrence plot for velocity signals of normal ossicular chain (first column), long process of the incus absent (second column), incus rebuild with bone cement (third column).

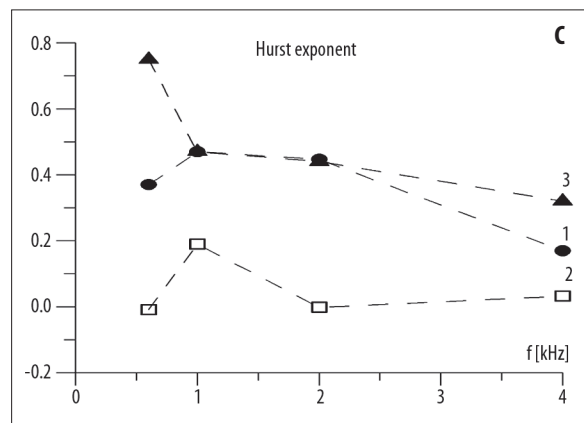
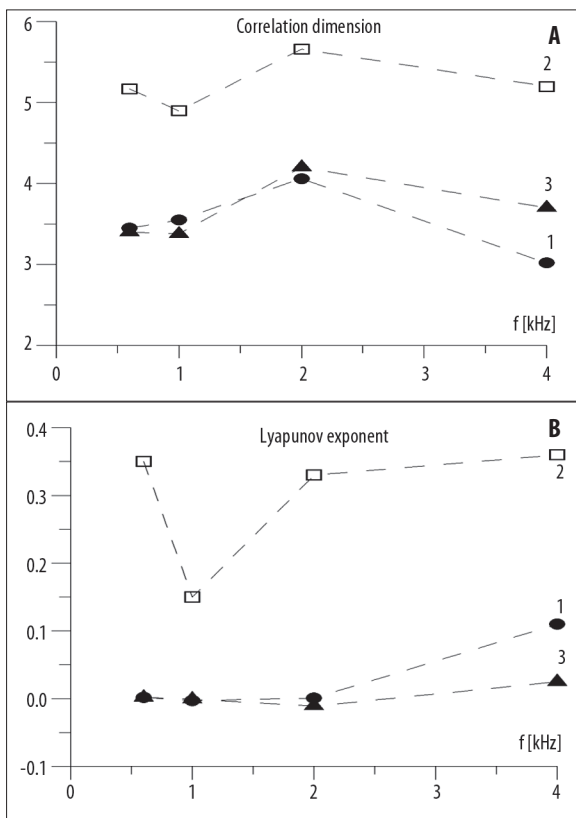


Figure 4. Comparison of Correlation dimension (a), Lyapunov exponent (b), Hurst exponent (c) for intact ossicular chain (1), long process of the incus absent (2) and incus rebuild with bone cement (3).

is observable (Figure 4A), suggesting stochastic (because of relatively big value of D_2) or chaotic behavior (because D_2 is not an integer number with an exception of 1 kHz when $D_2 \cong 5$). Analysis of Lyapunov exponent (λ) also suggests

irregular motion of ossicular chain (Figure 4B) when long process of the incus is absent. Theoretically, Lyapunov (λ) exponent greater than 0 means chaos, but in reality it is always greater than 0 for signals from real experiments. In our case $\lambda > 0.3$ may be taken as a limit value. The curve 1 and 3 (Figure 4B) indicate regular motion, while the curve 2 – irregular (chaotic), with the exception of 1 kHz where there motion is regular. The last analyzed indicator which can tell us about the relative tendency of the time series is Hurst exponent H (Figure 4C). The intact ossicular chain (No. 1) and incus rebuild with bone cement (No. 3) have the features of persistence ($H > 0.5$), while in the case of long process of the incus absent (2) $H < 0.2$, that means the time series is antipersistent.

The calculations of correlation dimension, Lyapunov and Hurst exponent are made with the aid of Chaos Data Analyser software; in our opinion they can be applied to diagnosing illness of the middle ear and to estimate the method of treatment of audition disorder.

Summarizing all investigations, the proposed approach proves to be useful and complementary for the method currently used in medical practice. Evaluation of vibration patterns in the middle ear supplements the classical approach to middle ear mechanics and looks at the problem from a different angle.

DISCUSSION

The methods of classical analysis of human ossicular chain vibrations take advantage of the transfer function between the input signal (sound) and output signal (displacement or velocity of the ossicles). It turns out that if we use only the transfer function, some interesting information about ossicles motion can be lost. Therefore, exploring a new method of analysis is well-grounded, especially comparing different methods of middle ear reconstruction. This paper points out that methods used thus far cannot be sufficient for proper analysis and should be complemented by using techniques from nonlinear mechanics such as phase portraits, recurrence plots, and Lyapunov and Hurst exponents. Introducing new methods of analysis, one can recognize different kinds of vibrations of the middle ear ossicles (periodic, quasi-periodic or irregular). That is not possible using only transfer function, which tells us only the height of the amplitude (or RMS) in relation to the sound source.

Taking results of investigations into consideration, one can conclude that for all analyzed frequencies, dynamical behavior of the system after the ossicular chain reconstruction is convergent with the normal ossicular chain. This means that the presented form of treatment, using bone cement, brings the expected positive results. Stapes vibrations are regular (harmonic), both in intact and reconstructed ossicular chain, whereas stapes motion in damaged ossicular chain seems to be irregular – stochastic or chaotic for 0.6 kHz. Phase portraits suggest that vibrations are stochastic, but further analysis with the help of recurrence plots,

and Lyapunov and Hurst exponents show that vibrations are indeed irregular, but at 1 kHz they are harmonic (regular RP, small λ). Such regular stapes vibrations can be caused by a sufficiently strong sound source.

CONCLUSIONS

The proposed new method of analysis allows us to distinguish various kinds of vibrations and gives us a look inside the dynamics. Among the proposed method of signal analysis, recurrence plots and Lyapunov exponents are the best to characterize ossicles vibrations and therefore can be used to demonstrate effectiveness of treatment. Vibrations of the stapes, when the incus long process is damaged, are small and irregular by nature, but can be regular for some specific frequencies if sound stimulus has enough energy expressed by high SPL.

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