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Elemental Research for Quantification of Eustachian Tube Insufflation Method

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***Abstract*—Commercial equipment is available for conducting Eustachian tube function tests but, generally, the Eustachian tube insufflation method doubles as a treatment and diagnosis. However, with the Eustachian tube insufflation method, the doctor merely performs the auscultation. The Eustachian tube insufflation sounds are not saved as data, and the diagnosis relies on the auditory judgment of the doctor. That is, the technique is not objective. To overcome these disadvantages, we set out to develop a system that would enable the objective evaluation of the Eustachian tube insufflation sounds. We sampled a wide range of Eustachian tube insufflation sounds and tried to identify the acoustic features of specific pathological conditions. However, it was so difficult to find the features of Eustachian tube insufflation sounds and to classify according to observation of spectra completely. Therefore, we proposed a method of inputting the frequency analysis results as feature vectors to a Self-Organizing Map (SOM). Our results confirmed that, when the maximum values of the spectra are normalized using the 0- to 5-kHz frequency analysis results, the normal sounds, stenosis, and crepitation could be classified.**

***Index Terms*—Eustachian tube, stenosis sound, health monitoring, self-organizing map**

I. INTRODUCTION

For a human to hear a sound, the sound waves must pass through the ear canal and vibrate the eardrum, and this vibration is transmitted to the inner ear through ossicles in the middle ear. If, however, the atmospheric pressure and middle ear pressure are not equal, the eardrum cannot vibrate properly, so that the sound is not transmitted correctly. To prevent this, the Eustachian tube maintains a balance between the atmospheric and the middle ear pressures. The Eustachian tube is an organ that connects the middle ear and epipharynx. In addition to its pressure-equalizing function, the Eustachian tube also expels foreign bodies and provides a defense function. This function plays an important role in maintaining the homeostasis of the middle ear, and since Eustachian tube dysfunctions lead to various diseases in the middle ear and the Eustachian tube itself, it is important to be able to evaluate the functions of the Eustachian tube [1]. Diseases associated with the Eustachian tube include Eustachian tube stenosis in which the tube narrows and has difficulty opening [2], patulous Eustachian tube in which the tube is permanently open [3], and otitis media with effusion in which fluid collects in the middle ear due to the compromised function of the Eustachian tube [4].

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Various methods of examining the Eustachian tube function have been proposed: an acoustic method, an impedance method, and a Eustachian tube-tympano-aerodynamic method [5]-[12]. To perform these examinations, equipment that enables the quantitative inspection of the Eustachian tube function is commercially available [13]. On the other hand, a method that uses Eustachian tube insufflation is widely used in practice. Eustachian tube insufflation works as follows: air is provided from the pharyngeal opening of the Eustachian tube into the Eustachian tube itself, and a doctor uses a rubber tube to listen to the sound of the air passing through the Eustachian tube [1]. The Eustachian tube insufflation method is superior to other methods such as the acoustic method in that the diagnosis also constitutes the treatment. Furthermore, the doctor confirm the hardness of the Eustachian tube or the exudation symptoms of the Eustachian tube and the middle ear cavity. However, there are some disadvantages: since the doctor merely performs auscultation, the Eustachian tube insufflation sounds are not saved as data, and as the diagnosis depends on the auditory judgment of the doctor, the objectivity is poor.

Therefore, in this research, we set out to quantify the Eustachian tube insufflation method and improve the objectivity and reliability of the diagnosis: we collected the Eustachian tube insufflation sound from a range of patients with Eustachian tube diseases and examined the characteristics of those sounds. However, it was so difficult to identify the characteristics by medical conditions from numerous data by observing method. Therefore, we also examined the feature extraction process for the classification of Eustachian tube insufflation sounds depending on medical conditions by the Self-Organizing Map (SOM).

The Maximum Entropy Method (MEM) was applied to the sampled Eustachian tube insufflation sounds to estimate their spectra. As the result, it was estimated that the difference in the frequency characteristics by medical conditions might not appear over 5 kHz. The obtained MEM spectra were used as the feature vectors and were classified with the SOM for evaluation.

II. EUSTACHIAN TUBE INSUFFLATION METHOD

In the Eustachian tube function test, the closing and opening of the Eustachian tube can be confirmed, but the hardness of the Eustachian tube and the exudation symptoms of the middle ear are difficult to confirm. Therefore, the Eustachian tube insufflation method is usually applied to the diagnosis of Eustachian tube diseases. The Eustachian tube insufflation method uses a metal Eustachian tube catheter to deliver air from a compressor, etc., into the Eustachian tube via the pharyngeal opening. The generated Eustachian tube insufflation sound is monitored by a doctor using a rubber tube called an otoscope. The tube used to deliver the air from the air compressor (Fig. 1) has a part with a hole, as shown in Fig. 2. The doctor uses this hole to adjust the pressure by covering it with his/her finger.

In the case of a healthy Eustachian tube, the Eustachian tube insufflation sound resembles a ball or tire deflating. However, for Eustachian tube stenosis, harmonic stenosis sounds (a high-pitched whistle) may be heard, or the insufflation sound may be erratic. If the stenosis is severe, there may be no discernable insufflation sound at all. On the other hand, if there is any secretion in the eardrum cavity or the Eustachian tube, crepitation or rales (gurgling or a crackly bubbling, respectively) may be heard. A patulous Eustachian tube produces an insufflation sound even when the insufflation pressure is low.

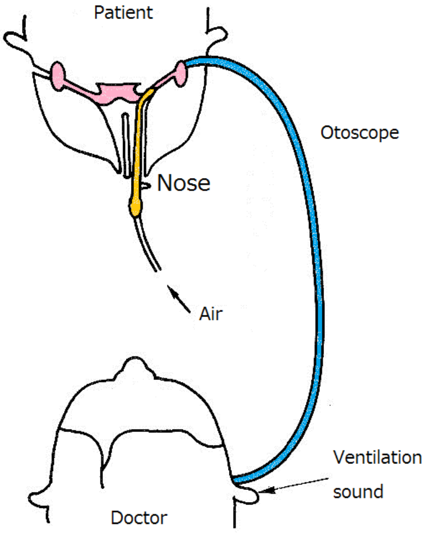


Figure 1. Eustachian tube insufflation method [14]

Figure 2. Pressure adjustment part

III. CONFIGURATION OF EQUIPMENT

A. *Configuration of Eustachian Tube Insufflation Sound Collection Equipment*

The Eustachian tube insufflation sound was recorded by inserting a silicon microphone (SP0103NC3-3) with an ear tip into the patient's ear canal. Next, using an NI9239 analog input module (National Instruments), A/D conversion was conducted at a sampling frequency of 50kHz and a quantization bit rate of 24 bits, and the results were input to a PC. The configuration of the microphone is shown in Fig. 3. It was configured so that the Eustachian tube insufflation sound is output to headphones while the sound is being recorded. This makes it possible to listen to the Eustachian tube insufflation sound in real time, so that it does not interfere with the application of the traditional Eustachian tube insufflation method.

Figure 3. Configuration of microphone

B. *Signal Processing Flow*

By observing the frequency analysis, it was estimated that the characteristics of abnormal Eustachian tube insufflation sounds might not be observed over 5kHz. Therefore, the collected insufflation sounds were down-sampled to a sampling frequency of 10kHz to reduce the amount of data, and then the frequency components of 5kHz or lower were used. Since the abnormal sound might be generated locally, if the entire spectrum of the collected Eustachian tube insufflation sounds were to be obtained, then the frequency characteristics of the abnormal sound would be diluted. For this reason, in this research, abnormal sounds were identified through auscultation, and then 0.1 s of data was extracted to use for feature identification. Next, frequency analysis was conducted using the Maximum Entropy Method (MEM), and the feature vectors were prepared and then classified with the Self-Organizing Map method (SOM).

C. *Maximum Entropy Method*

The maximum entropy method (MEM) was proposed by J. P. Burg in 1967 [15]. Akaike was also advocated as an “autoregressive model” [16]. It is based on the fact that spectra can be estimated by applying an autocorrelation function with a large lag which cannot be measured with the limited measurement data, such that the information entropy is maximized. Compared to the fast Fourier Transform Method (FFT), the resolution of the spectra is extremely high. It is also relatively resistant to noise, and thus is able to estimate spectra even when the data length is short relative to the signal period.

The most important point regarding MEM is that the use of an autoregressive model is assumed for the given measurement data. The autoregressive model is a stochastic process model, and is expressed as follows:

$$x_k = -\sum_{i=1}^{m} a_{mi} x_{k-i} + n_k \tag{1}$$

However, $x_k \left(= x(k\Delta t)\right)$ is the observed time series measurement signal, while n_k expresses stationary white noise independently of $x_l \left(l < k\right)$. m is the order of the autoregressive model, while a_{mi} is the m^{th} autoregressive coefficient. If we express the autocorrelation function R_i of measurement signal x_k:

$$R_i = R\left(i\Delta t\right) \equiv E\left\{x_k x_{k-i}\right\} \tag{2}$$

$E\left\{\ \right\}$ is the expected value By solving for the expected value by multiplying both sides of Equation (1) by x_k, the following equation is obtained.

$$\begin{aligned} R_0 = E\left\{{x_k}^2\right\} &= -\sum_{i=1}^{m} a_{mi}\cdot E\left\{x_k x_{k-i}\right\} + E\left\{x_k n_k\right\} \\ &= -\sum_{i=1}^{m} a_{mi} R_i + E\left\{{n_k}^2\right\} \end{aligned} \tag{3}$$

However, n_k is independent of $x_l\left(l < k\right)$. Similarly, by solving for the expected value by multiplying both sides of Equation (3) by x_{k-1}, x_{k-2}, and x_{k-m}, the following matrix equation is obtained:

$$\begin{bmatrix} R_0 & R_1 & \cdots & R_m \\ R_1 & R_0 & \cdots & R_{m-1} \\ \vdots & & & \vdots \\ R_m & \cdots & \cdots & R_0 \end{bmatrix} \begin{bmatrix} 1 \\ a_{m1} \\ \vdots \\ a_{mm} \end{bmatrix} = \begin{bmatrix} P_m \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4}$$

P_m is a variance of the stationary white noise $\left(E\left\{{n_k}^2\right\} = \sigma^2\right)$. Also, by using the Wiener-Khinchine formula, the relationship between the autoregressive model $\left\{a_k\right\}$ and the power spectrum $S\left(\omega\right)$ can be presented.

$$S\left(\omega\right) = \frac{P_m\cdot\Delta t}{\left|1 + \sum_{i=1}^{m} a_{mi} e^{-j\omega i\Delta t}\right|^2} \tag{5}$$

The autocorrelation function $R_0, R_1, \cdots, R_m$ is obtained from the measured signals, and by substituting this into Equation (4), the autoregressive coefficient $a_{m1}, a_{m2}, \cdots, a_{mm}$ and P_m can be estimated. By substituting this into Equation (5), the power spectrum of the observed waveform $S\left(\omega\right)$ can be estimated as a continuous function of each frequency ω.

D. *Self-Organizing Map*

The SOM was proposed by T. Kohonen [17]. The SOM uses the algorithm of unsupervised and competitive neighborhood learning, and is a two-layered neural network composed of input and output layers (competitive layers). The output layer is normally set to two- or three-dimensions for visualization, with a configuration in which nodes are aligned on a grid. When the input is an n^{th}-dimensional vector, each node of the output layer has an n^{th}-dimensional reference vector. When an input vector y_p is applied, the node that is the most similar to y_p, i.e., that with a reference vector having the minimum Euclid distance, wins, leading to the output of y_p. Learning in the SOM changes the reference vector, meaning that the reference vector of the winning node approaches y_p, while the reference vectors of the neighboring nodes also approach y_p. As such, by learning the collection of input vectors at a high dimension, an output map can be obtained in which similar sample groups are grouped at the same position on the map (node) or in the neighborhood.

In this research, the output layer was a two-dimensional map measuring 30×30, the learning rule consisted of batch process learning in which corrections are made after all of the learning sets are input, and a gauss function was used for the neighborhood function. Since the goal of this study was not to improve the SOM algorithm, details of the SOM algorithm are omitted.

IV. RESULTS AND DISCUSSIONS

A. *Frequency Analysis of Collected Eustachian Tube Insufflation Sounds*

The collected Eustachian tube insufflation sounds were categorized into three main type (normal, stenosis, crepitation) by a doctor with auscultation of Eustachian tube insufflation method. Furthermore, we tried analysis the sounds, in order to find the characteristics by MEM method. The MEM spectra samples of three types are shown in Fig. 4 to Fig. 6. These figures are especially typical. The Autoregression (AR) degree is 40 th-order.

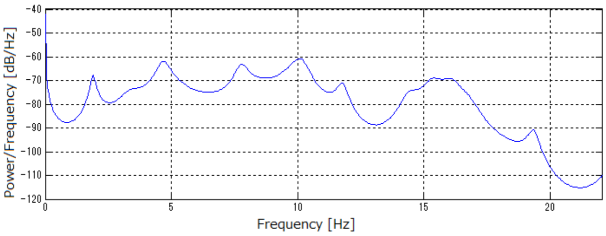


Figure 4. MEM of normal sound

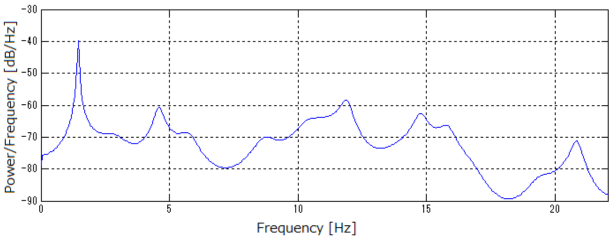


Figure 5. MEM of stenosis sound

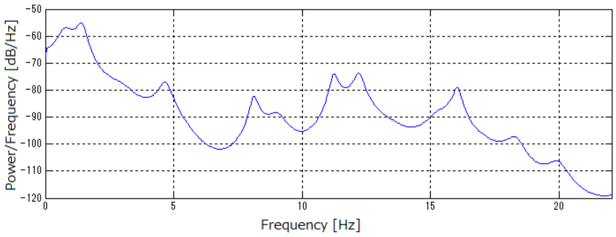


Figure 6. MEM of crepitation

- Normal sounds

In Fig. 4, the spectrum peaks are observed at around 2, 5, 8, 10, 12, 15, and 20kHz. However, there are individual differences. Also, the sound was stationary in that while an air pressure was applied, its frequency component did not exhibit any notable fluctuations.

- Stenosis sounds

Stenosis sound occurs locally among the normal sound in the frequency band and, in comparison with the normal sounds, peaks at around 2kHz have an especially high intensity in Fig. 5. By observing the MEM spectra of all data, at least, the peaks were confirmed among 500Hz to 3kHz.

- Crepitation

Interruptions in the insufflation sounds could be confirmed in the time series waveform. In Fig. 6, its spectrum indicates that the intensity in the bandwidth at 3kHz or lower is high and, compared to the normal sound (Fig. 4), the bandwidth below the peak at around 2kHz is not attenuated. However, there are individual differences.

Thus, it was so difficult to find the features of Eustachian tube insufflation sounds and to classify according to observation of MEM spectra completely, because there are individual differences. However, the characteristics of Eustachian tube insufflation sounds seemed to exist in 5kHz or lower probably. In other words, we assumed that the feature probably appeared in MEM spectra in 5kHz or lower. Therefore, we also examined the feature extraction process for the classification of Eustachian tube insufflation sounds depending on medical conditions by SOM, using MEM spectra.

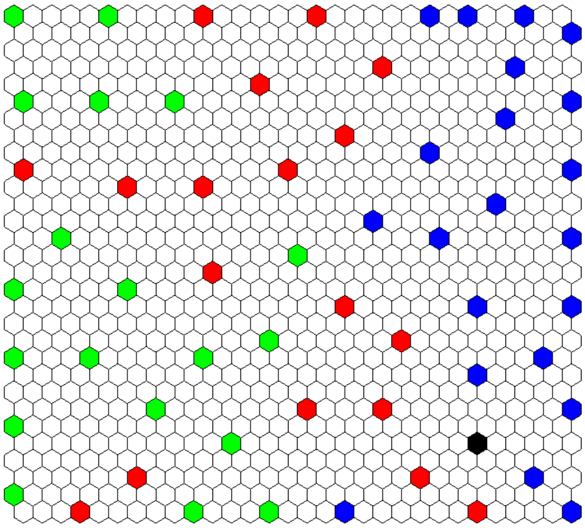
B. *Classification by SOM*

We were able to collect data from 59 sounds. From the data, we extracted 22 normal examples, as well as 18 examples of stenosis, and 19 crepitation, obtained through auscultation and tympanometry, and applied them to the SOM classification. Feature vectors were prepared under the following conditions, and input to the SOM.

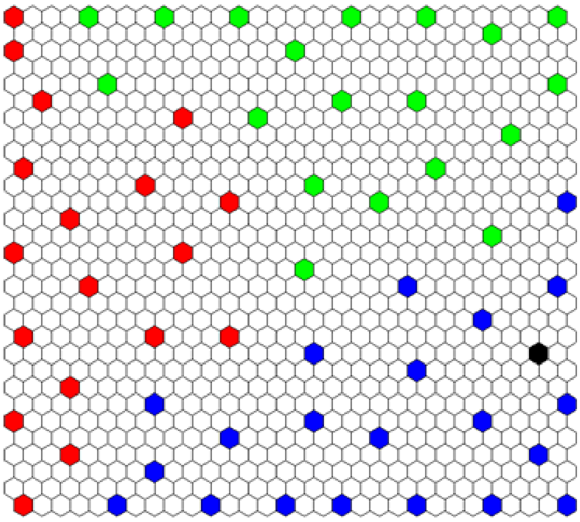
(a) A MEM spectrum of a 250-point averaging of 0 – 5000Hz on a linear frequency axis.
(b) A MEM spectrum of a 250-point averaging of 0 – 5000Hz on a linear frequency axis, normalized to 0 – 1.

SOM results are shown in Fig. 7. The SOM classifies data only according to the inputted feature vector, and it does not use teach signals. After the end of the leaning of SOM, the outputs were colored according to the result diagnosed by a doctor beforehand.

(a) show that the normal sounds (blue) are separated from other abnormal sounds except for one normal sound, but stenosis (red) and crepitation (green) do not exhibit a clear grouping, although there do appear to be some clusters. On the other hand, in (b), the minimum value of the MEM spectra is subtracted from the whole, while dividing the whole by the maximum value of the spectra to normalize the MEM spectra to 0 – 1. By normalization (b), the Eustachian tube insufflation sounds were clearly classified into three clusters. Normalization is effective in using spectral shape for a classification preponderantly. In other words, the normalization would enable a clear examination of the spectrum shapes, regardless of the volume of insufflation sounds. Therefore, we can say that the MEM spectra (0 – 5kHz) include the feature and the spectral shape is important for classifying the Eustachian tube insufflation sounds.



(a) Without normalization



(b) Normalized

Figure 7. SOM output results

Blue: normal sounds, Red: stenosis sounds, Green: crepitation, and Black: diagnostic data (normal sound)

V. SUMMARY

Commercially available Eustachian tube function test equipment may be able to confirm the opening and closing of the Eustachian tube, but cannot be used to confirm the hardness of the Eustachian tube or the exudation symptoms of the Eustachian tube and the middle ear cavity. Therefore, generally, diagnosis and treatment are conducted using the Eustachian tube insufflation method. With this method, however, only the doctor performs auscultation, meaning that the Eustachian tube insufflation sound is not saved as data. The diagnosis is therefore subjective and the same sound may be diagnosed differently depending on the doctor.

In our research, we set out to quantify the Eustachian tube insufflation method, with a goal of improving the objectivity and reliability of the diagnosis, and examined the feature extraction processing by MEM spectra. However, it was so difficult to find the features of Eustachian tube insufflation sounds and to classify according to observation of spectra completely. Therefore, we proposed a method of inputting the MEM spectra as feature vectors to a SOM.

The results classified by SOM showed that, by normalizing the MEM spectra, three types of sounds that were not separated when un-normalizing were output as separate groups, thus indicating the efficacy of the normalizing method. Therefore, we believe that the MEM spectra include the feature and the feature appears in the shapes of spectra, regardless of the volume of insufflation sounds.

In our future work, we will increase the amount of data, and any data that is not used for learning will be input to the SOM. By examining the output, the objectivity of our proposed method should be discussed. Also, the proposed method is likely to be able to produce a diagnosis with the extracted parts of the waveform of insufflation sounds, but a diagnosis cannot be produced with the overall sound, prior to the extraction. Thus, processing capable of overcoming this issue should be devised. Furthermore, the hardness of the Eustachian tube or the exudation symptoms of the Eustachian tube and the middle ear cavity are have to inquire.

This research was done by obtaining the approval of the Ethics Committee of faculty of medicine, University of Yamanashi, Japan.

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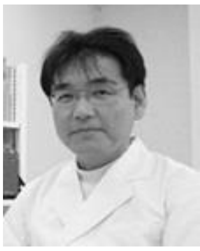

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