# A simplified measurement method of TMTF for hearing-impaired listeners

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It is difficult to understand speech for listeners with reduced temporal resolution. To measure the auditory index of temporal resolution in clinical diagnosis, a novel measurement method was proposed. It is called a simplified measurement method of temporal modulation transfer function (S-TMTF). This method is based on measurement of temporal modulation transfer function (TMTF). The novelty of S-TMTF lies in the use of only two thresholds for estimation of peak sensitivity and 3-dB cutoff frequency. One is a threshold of modulation depth and the other is a threshold of modulation frequency. In this study, to evaluate the practicability and accuracy of peak sensitivity and 3-dB cutoff frequency, both S-TMTF and TMTF were measured for normal-hearing and hearing-impaired subjects. Results of S-TMTF were significantly correlated with that of TMTF and the measurement time of S-TMTF could be shortened to one fourth of the time for TMTF. Furthermore, the measurement time will be shortened by using the method of limits. S-TMTF would be applied for clinical diagnosis of hearing impairment.

## INTRODUCTION

It is well known that temporal resolution is reduced for hearing-impaired listeners. Narne and Vanaja (2009) said that it is difficult to understand speech for listeners with reduced temporal resolution. To measure the auditory index of temporal resolution, gap detection threshold (GDT) and temporal modulation transfer function (TMTF) are often used in psychoacoustical experiments (Shen and Richards, 2013).

GDT is the threshold of time for detecting a silent interval embedded between two noise bursts. Penner (1977) reported that, for normal-hearing subjects, the threshold of time is usually approximately 3 ms but that it is larger for the hearing impaired. TMTF is the threshold of modulation depth as a function of modulation frequency. Usually, seven thresholds of modulation depth are measured for estimation of two parameters. TMTF can express sensitivity to modulation depth and detection ability of fast modulation frequency (Formby and Muir, 1988; Eddins, 1993). These abilities

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are called the peak sensitivity and 3-dB cutoff frequency, respectively. Bacon and Viemeister (1985) reported that the thresholds of modulation depth for hearing-impaired listeners were increased more than for normal-hearing listeners. If TMTF is measured in clinical diagnosis, the auditory characteristic for hearing-impaired might be described more precisely. Furthermore, this information might denote hearing-aid fitting parameters or be applied for new hearing prostheses. Therefore, applying TMTF in clinical diagnosis is desired. It is difficult to apply for clinical diagnosis since the measurement of TMTF is more time consuming than that of GDT.

In this paper, for shortened measurement time, a simplified measurement method of TMTF (S-TMTF) is proposed. This method needs two measurement points, one is a threshold of modulation depth at a lower modulation frequency, and the other is a threshold of modulation frequency for which a signal with sufficient modulation depth is used. For investigation of practicability and accuracy of S-TMTF, the measurement time and two parameters of S-TMTF were compared with TMTF for normal-hearing and hearing-impaired subjects.

## OUTLINE OF CONVENTIONAL TMTF

The measurement of TMTF used a sinusoidal-amplitude-modulated broadband noise. Modulation depth thresholds were measured as a function of modulation frequency. Figure 1 shows experimental data of TMTF for normal-hearing and hearing-impaired listeners. The ordinate indicates modulation depth thresholds and the abscissa shows modulation frequency. The modulation depth threshold is often measured using modulation frequencies of 8, 16, 32, 64, 128, 256, 512 Hz (Eddins, 1993; Shen and Richards, 2013). Thresholds are expressed in decibels as $20\log_{10}(m)$, where $m$ is the modulation-depth parameter. When the modulation-depth parameter $m$ is 1.0, the signal has a modulation depth of 100%, i.e., the modulation depth is expressed as 0 dB, the carrier level falls to zero and rises to twice its non-modulated level. Additionally, when $m$ is 0.5 and 0.1, the modulation depths is expressed as -6 dB (50%) and -20 dB (10%), respectively. Modulation-depth thresholds are fairly constant from a 8-Hz modulation frequency to about 50 Hz. Beyond 50-Hz modulation frequency, the threshold increases more slowly at a rate of about 3 dB per octave of modulation frequency (Bacon and Viemeister, 1985). For a hearing-impaired listener, modulation-depth thresholds increase less than that of normal-hearing listeners, as shown in Fig. 1. This difference expresses a degraded ability of temporal resolution (Zeng *et al.*, 1999). These thresholds are very well fitted with a first-order Butterworth filter. Formby and Muir (1988) and Eddins (1993) modeled the TMTF using a function of the form

$$\phi(f_m) = L_{ps} - 10\log_{10}(1/(1+(f_m/f_c)^2)) \qquad \text{(Eq. 1)}$$

where $\phi(f_m)$ denotes the modeled TMTF, $L_{ps}$ denotes peak sensitivity (dB, 20 log $m$), $f_c$ denotes the 3-dB cutoff frequency, $f_m$ denotes modulation frequency. For normal-hearing listeners, typically $L_{ps}$ is approximately $-24$ dB and $f_c$ is approximately 140 Hz (Shen and Richards, 2013).

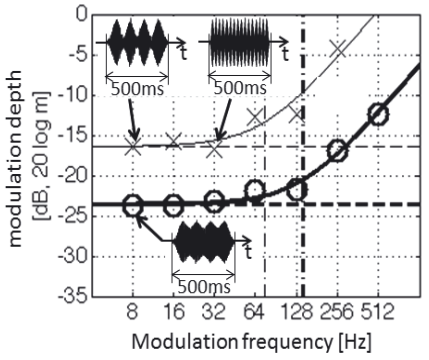


**Fig. 1:** Example of TMTF. The ordinate denotes modulation depth and the abscissa denotes modulation frequency. The circles and heavy lines denote the results of normal-hearing listeners and the x-marks and narrow lines denote the results of hearing-impaired listeners. Solid lines denote the model of TMTF, dashed lines denote $L_{ps}$, and chain lines denote $f_c$. The waveform of the sinusoidal-amplitude-modulated noise is indicated for different conditions.

## A PROPOSED SIMPLIFIED MEASUREMENT METHOD OF TMTF

For shortened measurement time, a simplified measurement method of measurement of TMTF (S-TMTF) is proposed. S-TMTF is based on the conventional method of TMTF. The characteristic of S-TMTF lies in the use of only two thresholds for estimating both $L_{ps}$ and $f_c$. One is a modulation-depth threshold at a lower modulation frequency and the other is a modulation-frequency threshold at fixed modulation depth. This method is fast and is almost as accurate as a conventional TMTF measurement. A procedure of S-TMTF is shown as follows:

**Step 1 :** A modulation depth threshold $\phi(\alpha)$ is measured, where $\alpha$ is an arbitrary modulation-frequency value. Usually, $\alpha$ is a lower modulation frequency (e.g., 8 Hz). The measured $\phi(\alpha)$ is considered to be $L_{ps}$ in S-TMTF.

**Step 2 :** Modulation frequency $f_{m1}$ is measured at the modulation depth which is set at $\phi(\alpha)+\beta$, where $\beta$ is an arbitrary value. The value of $\phi(\alpha)+\beta$ should be set at an audible modulation depth at a lower modulation frequency.

**Step 3 :** $f_c$ is estimated from substituting $L_{ps}$ and $f_{m1}$ into Eq. 2.

$$f_c = f_{m1}(10^{-L_{ps}/20} - 1)^{-1/2} \qquad \text{(Eq. 2)}$$

| Sub. | Age | Sex | Ear | Frequency (Hz) 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | (dB HL) | | | | | | |
| HI-A | 82 | F | L | 45 | 45 | 45 | 55 | 65 | 70 | 80 |
| HI-B | 66 | F | L | 70 | 85 | 80 | 75 | 80 | 75 | 85 |
| HI-C | 68 | F | R | 50 | 60 | 55 | 55 | 60 | 65 | 75 |
| HI-D | 72 | F | R | 65 | 70 | 70 | 75 | 80 | 75 | 100 |
| HI-E | 84 | F | L | 60 | 65 | 60 | 55 | 60 | 75 | 85 |
| HI-F | 71 | F | R | 60 | 55 | 55 | 55 | 65 | 55 | 85 |
| HI-G | 79 | M | R | 50 | 65 | 55 | 40 | 55 | 55 | 75 |
| HI-H | 85 | F | R | 60 | 60 | 55 | 60 | 65 | 75 | 85 |
| HI-I | 86 | F | L | 70 | 70 | 70 | 65 | 75 | 70 | 85 |
| HI-J | 83 | M | L | 70 | 70 | 65 | 65 | 70 | 65 | 70 |
| HI-K | 82 | M | R | 35 | 45 | 50 | 80 | 95 | 90 | 80 |
| HI-L | 79 | F | R | 30 | 40 | 50 | 55 | 60 | 65 | 75 |
| HI-M | 75 | M | L | 55 | 45 | 45 | 55 | 70 | 70 | 85 |

**Table 1:** Profiles and hearing thresholds for tested ears of individual hearing-impaired subjects.

## EXPERIMENT

$L_{ps}$ and $f_c$ were measured by both TMTF and S-TMTF. Results were compared and the measurement practicability and accuracy of S-TMTF was evaluated.

### Subjects

16 normal-hearing subjects and 13 hearing-impaired subjects participated. The age of normal-hearing subjects ranged from 25 to 43 years. All subjects had hearing thresholds better than 15 dB HL at all audiometric frequencies in the tested ear. The age of hearing-impaired subjects ranged from 66 to 86 years. Table 1 shows the individual profiles and hearing thresholds for hearing-impaired subjects.

### Stimuli and equipment

A broadband noise (20-14000 Hz) was generated and controlled digitally. The duration of the noise was 500 ms, including 2.5 ms rise/fall cosine ramps. The noise was presented from a personal computer with a 16-bit digital-to-analog converter (Roland QUAD-CAPTURE) to the subject's tested ear via supra-aural headphones. Sony MDR-V6 headphones and Sennheiser HD 380PRO headphones were used for normal-hearing and hearing-impaired listeners, respectively. The presented level was fixed at 60 dB SPL for normal-hearing and fixed at 20 dB SL for hearing-impaired subjects.

### Procedure of modulation-depth threshold for S-TMTF and TMTF

For S-TMTF, the modulation-depth threshold was measured at 8 Hz, i.e., the value of $\alpha$ was set at 8 Hz. For TMTF, the thresholds of modulation depth were measured at seven modulation frequencies. These frequencies were set at 8, 16, 32, 64, 128, 256, and 512 Hz. In this study, the modulation-depth threshold at 8 Hz was reused as the threshold in the S-TMTF method. Detection thresholds were obtained using an adaptive, three-interval, three-alternative, forced-choice procedure (3I, 3AFC), with a two-down and one-up rule tracking the 70.7% point on the psychometric function (Levitt, 1971). Listeners did not receive any feedback concerning the correct interval after each trial. To shorten measurement time, a detection-threshold task was carried out once, i.e., there was no repeated measurement. For modulation-depth thresholds for S-TMTF and TMTF, the modulation depth was started at 0 dB. Twelve reversals were obtained in a given task, and the threshold estimation for the task was taken as the mean value of the last eight reversals. The step-size was set to 4 dB at the first four reversals and 2 dB thereafter.

### Procedure of modulation-frequency threshold for S-TMTF

The modulation-frequency threshold was measured at modulation depth $\phi(\alpha)+\beta$, where $\beta$ was the absolute value of $L_{ps}/2$. Detection thresholds were obtained with the same procedure as the modulation-depth threshold. The modulation frequency was started at 8 Hz. The step-size was set to 2 octaves at the first four turnarounds and 1 octave thereafter.

## RESULTS

The measurement time of S-TMTF was approximately 10 minutes and the measurement time of TMTF was approximately 40 minutes for each subject. The measurement time of S-TMTF was thus shortened to one-fourth of the time of TMTF. Figure 2(a) shows the correlation diagram of $f_c$ and (b) shows $L_{ps}$ estimated from S-TMTF and TMTF for normal-hearing and hearing-impaired subjects. The ordinate denotes values estimated from S-TMTF and the abscissa shows values estimated from TMTF. Correlation coefficients for $f_c$ and $L_{ps}$ were 0.89 ($p < 0.01$) and 0.92 ($p < 0.01$), respectively. Both parameters estimated from S-TMTF were significantly correlated with TMTF. For $f_c$, differences between S-TMTF and TMTF were within the smaller step-size for all subjects. For $L_{ps}$, differences between S-TMTF and TMTF were within the smaller step-size for 25 out of 29 subjects.

## DISCUSSION

The measurement time of S-TMTF was 10 minutes and was shortened to one-fourth of the time of TMTF for normal-hearing and hearing-impaired subjects. This result shows that it is possible to measure in clinical diagnosis. However, there are other clinical measurements such as an audiogram and speech-intelligibility tests at the same consultation session. It is desirable to shorten the measurement time of S-TMTF. In a

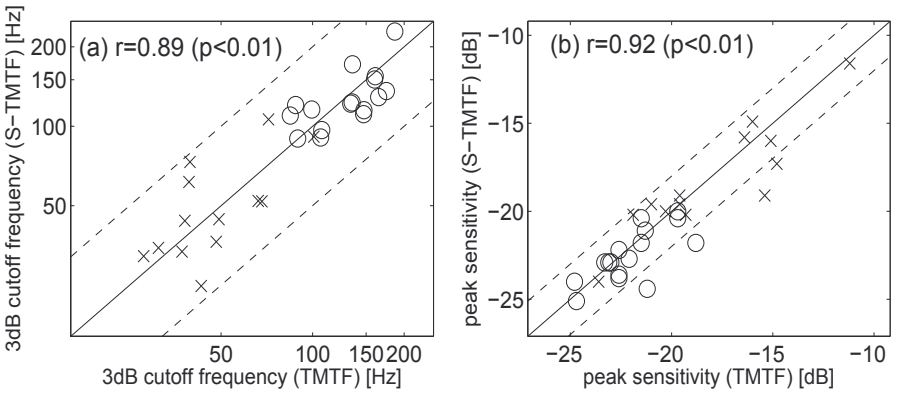


**Fig. 2:** Correlation diagrams between S-TMTF and TMTF for normal-hearing and hearing-impaired subjects. (a) Correlation diagram of $f_c$. (b) Correlation diagram of $L_{ps}$. The ordinate denotes values estimated from S-TMTF and the abscissa denotes values estimated from TMTF. The circles denote results of normal-hearing subjects and the x-marks denote results of hearing-impaired subjects. Dashed lines denote smaller step-size ranges for each measurement.

further investigation, detection thresholds will be obtained using the method of limits rather than the 3AFC for shortened measurement time.

The $f_c$ and $L_{ps}$ estimated from S-TMTF were significantly and highly correlated with TMTF. The accuracy of S-TMTF was confirmed because the differences in $f_c$ between S-TMTF and TMTF were within the smaller step-size for all subjects, and the differences in $L_{ps}$ were within the smaller step-size for 25 subjects out of 29 subjects (86%). On the other hand, differences in $L_{ps}$ between the two methods were out of the smaller step-size range for 4 subjects out of 29 (2 normal-hearing and 2 hearing-impaired subjects). On results of remeasurement, differences were within the smaller step-size for the mentioned subjects with normal hearing. The thresholds may need to be measured twice or more to determine more accurate results, as reported by Bacon and Viemeister (1985). The sufficient performance, however, was obtained from only one determination, as mentioned above.

## SUMMARY

To measure the auditory index of temporal resolution in clinical diagnosis, a simplified measurement method of temporal modulation transfer function (S-TMTF) was proposed. S-TMTF needs only two thresholds, one is a threshold of modulation depth at 8 Hz and the other is a threshold of modulation frequency for which a signal with sufficient modulation depth was used. To evaluate the measurement practicability and accuracy of S-TMTF, $f_c$ and $L_{ps}$ were measured using S-TMTF and TMTF. The

results showed that (1) the measurement time of S-TMTF was 10 minutes which is one-fourth of the time of TMTF, (2) two parameters estimated from S-TMTF were significantly correlated with TMTF for normal-hearing and hearing-impaired subjects. S-TMTF was fast and was almost as accurate as conventional TMTF. S-TMTF would be applied for clinical diagnosis of hearing impairment.

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