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Original Article

Age-Related Changes in Sound Image Localization during Lateral Gaze

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ABSTRACT

Introduction: Sound image localization is affected by eye position; however, the effect of aging on this process is unclear. This study aimed to examine the effects of age-related changes on sound image localization during lateral gaze.

Methods: The subjects were 34 healthy individuals (8 men and 26 women) aged 23-63 years. The binaural input sound was set to 500 Hz band noise at 50 dB, the time difference was set to 100 μs with an audiometer, and the interaural time difference discrimination threshold was measured. A sawtooth wave was recorded when the subject changed the time difference between the left and right input sounds and moved the sound image to the center. During the measurement, the subject gazed at 0-30° to the right or 30° to the left.

Results: The deviation of the medial axis during gaze was significantly higher in the middle-aged and elderly group (patients aged ≥40 years) than in the young age group (patients aged <40 years), but there was no significant difference in the deviation ratio between both groups at 0° gaze. There was no significant between-group difference in the amplitude.

Conclusions: The medial axis is more significantly deviated in the gaze direction in the middle-aged and elderly group than in the young age group. This indicates that eye position interference has a greater effect on sound localization in middle-aged and elderly people.

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KEYWORDS: sound image localization, eye position, gaze, age, interaural time difference

Introduction

Sound source localization, that is, recognition of the direction of the sound source through bilateral hearing, allows animals to be aware of the direction of sound and enhances their spatial perception, as well as vision, vestibular sensation, and deep perception.[1–3] Sound image localization is another sense of sound direction recognized through binaural hearing. Sound image localization is the formation of an intracranial sound image by receiving sound input from both ears, and sound source localization and sound image localization have been reported to be closely similar.[4] However, sound source localization is measured in a large anechoic chamber with speakers around the subject, whereas sound image localization is measured by listening to the sound output from the audiometer headphones with

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Table 1 Clinical background of the two groups.

(a) Young age group patient background

Age (years)	Number	Gender	Hearing	Visual acuity	Comorbidities
20s	8	Male, 1/female, 7	All normal	All normal	None
30s	7	Male, 2/female, 5	All normal	All normal	None

(b) Middle- and elderly age group background

Age (years)	Number	Gender	Hearing	Visual acuity	Comorbidities
40s	8	Male, 1/female, 7	All normal	All normal	None
50s	7	Male, 4/female, 3	All normal	All normal	None
60s	4	Male, 0/female, 4	All normal	All normal	None

The subjects are selected with normal hearing (hearing threshold 30 dB or less at 500 Hz) and normal visual acuity (binocular visual acuity 0.7 or higher). All subjects have no medical history.
(a) Young age group background. (b) Middle-aged and elderly group background.

both ears. Further, sound image localization does not require a large space and does not require special inspection equipment; therefore, it is more widely used clinically. Considering that the intensity and timing of the sound emitted from the binaural speakers can be changed by computer control in the sound image localization test, the interaural time difference discrimination (ITD) and interaural level difference discrimination (ILD) can be measured independently.[4]

Sound image localization in binaural hearing is recognized by auditory information processing in the superior olivary complex, where the left and right auditory afferent fibers first meet. Information is then sent to the medial geniculate body through the inferior colliculus.[5–7] Therefore, it is clinically used for the diagnosis of posterior labyrinthine deafness, such as acoustic neuroma.[8] There have been recent reports that the superior colliculus is involved in the localization and direction of the sound.[9, 10] Visual sense, vestibular sense, deep perception, and hearing, which compose spatial sense, have been found to interfere with each other.

Sound image localization is affected by eye position and gaze.[9, 11] Hisamatsu et al. investigated changes in the sense of direction with aging by examining sound image localization and found that the ITD threshold increases with age.[8] However, the effects of aging-related interference during lateral gaze have not been investigated. Thus, this study aimed to examine the effects of age-related changes in sound image localization during lateral gaze. It is said that vestibular dysfunction begins to appear gradually from the 40s, and according to a health survey conducted in the United States,[12] about 20% of people in their 40s have vestibular dysfunction. Therefore, we set the purpose of investigating whether or not there is a difference due to aging when gaze stimulation is applied between those under 40 years old and those over 40 years old.

Methods

Subjects

The subjects were 34 individuals with normal hearing and visual acuity (8 men and 26 women; mean age, 42.3 years [range, 23-63 years]). They were divided into two groups according to age as the young age group (i.e., those aged $<$40 years) and the middle-aged and elderly group (i.e., those aged ≥40 years). The clinical background of the two groups is shown in Table 1.

Interaural time difference discrimination measurement

The ITD threshold was measured using an audiometer (RION AA-H1) in a soundproof room. The subject was given a switch in both hands, and the sound stimulus was 500 Hz band noise at 50 dB delivered through headphones. The sound image was moved by gradually increasing the time difference at 100 μs/s. The subject was instructed to immediately press the right switch when he/she felt that the medial axis of the sound was tilted to the right from the midline and to press the left switch when he/she felt that the medial axis of the sound was tilted to the left of the midline. The change in the sound image was recorded as a sawtooth wave on the recording paper.

Interaural time difference discrimination threshold measurement under lateral gaze

The subjects were instructed to gaze at the marks with a diameter of 40 mm installed at 168 cm in front of the eyes at 0° and 30° to the right and 30° to the left in the sitting position. The ITD threshold was then measured. The back of the head was fixed to a pole to suppress head movement during lateral gaze (Fig. 1).

The amplitudes of the four sawtooth waves of 0° and left and right 30° gazes were measured. In addition, the average value and standard deviation of the ITD thresholds were calculated. The median plane deviation (left-right deviation ratio) of the sound image was calculated as follows: of the first four sawtooth waves from the start of the inspection, the length of the wave from left to right and from right to left were measured, and the sum of each was then calculated (Fig. 2). The deviation ratio was calculated by dividing the sum from left to right with the sum from right to left, and the mean and standard deviation for each group were calculated. The means and standard deviations of the discrimination threshold and deviation ratio were finally compared between the young group and the middle-aged and elderly group.

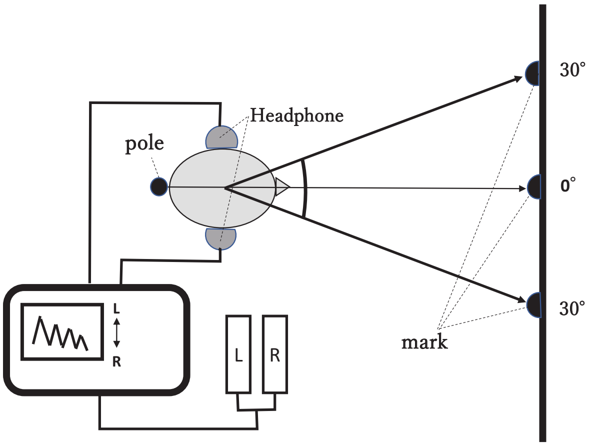

Fig. 1 Schematic drawing of the laboratory.
The subjects are instructed to gaze at the marks with a diameter of 40 mm installed at 168 cm in front of the eyes, at 0°, 30° to the right, and 30° to the left in the sitting position. The subject is given a switch in both hands, and the sound stimulus of 50 dB, 500 Hz band noise is heard while wearing headphones.
In addition, the back of the head is fixed to a pole to suppress head movement during lateral gaze.

Statistical analyses

The ITD and ILD thresholds were analyzed using the Mann-Whitney U test. The correlation between the subject's age and the deviation ratio was evaluated by Spearman's ordinal correlation coefficient. All statistical analyses were performed using EZR ver1.54 (Jichi Medical University at http://www.jichi.ac.jp/saitama-sct/SaitamaHP.files/statmedEN.html).[13] A *p*-value of <0.05 was considered statistically significant.

Ethics

The study protocol was approved by the Institutional Review Board of Toranomon Hospital (approval number: 2092) and was conducted according to the tenets of the Declaration of Helsinki and its later amendments. All procedures were fully explained to the subjects. Written informed consent was obtained from all participants involved in the study.

Results

Changes in sound image discrimination threshold

The age-specific sawtooth waves obtained varied greatly among subjects in the same age group. The amplitude in the young age group ranged from 225 to 662 µs (average, 490 µs), and from 250 to 1300 µs (average, 641 µs) in the middle-aged and elderly group, showing large individual differences. However, no-age related significant dif-

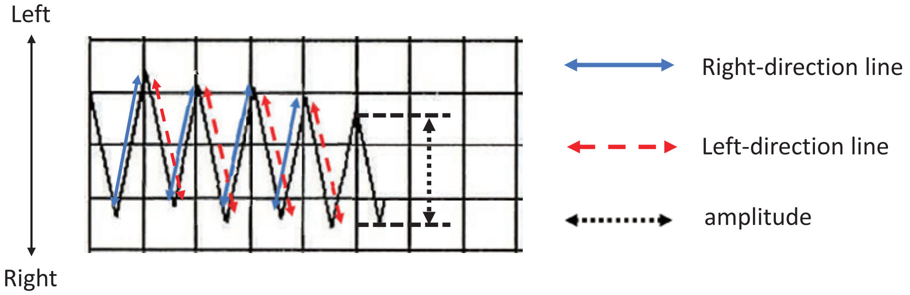

Fig. 2 The sawtooth waves shifted to the right side in the ITD test.
The length of the right side (line drawn toward the right) and of the left side (line drawn toward the left) is measured in four successive waves. The sift ratio for the sawtooth waves is calculated based on the total length of the lines drawn toward the right and left.

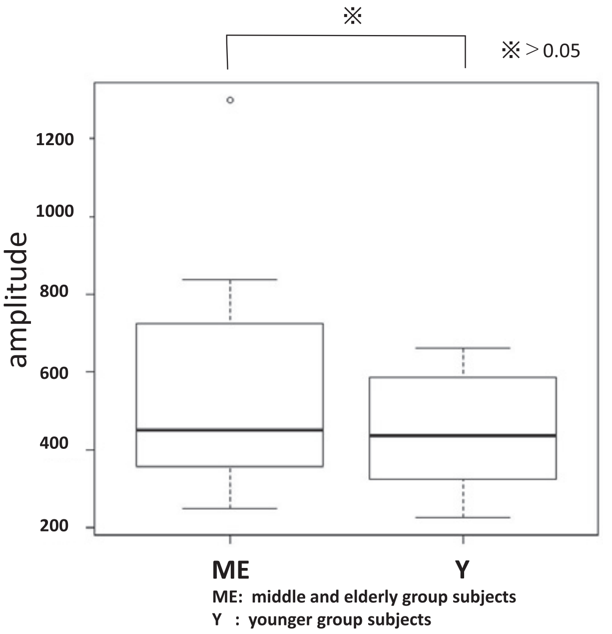

Fig. 3 Sound image discrimination threshold.

ferences in amplitude were observed (Fig. 3).

Deviation of the median plane of the sawtooth wave

At 0° gaze, there was no significant difference in the deviation ratio between the young age group and the middle-aged and elderly group. However, under the right 30° gaze and left 30° gaze conditions, the deviation of the median plane in the gaze direction was significantly larger in the middle-aged and elderly group (Fig. 4).

The correlation between the subject's age and the deviation ratio

When the correlation between the subject's age and the deviation ratio was evaluated by Spearman's ordinal correlation coefficient, a weak correlation was found in the deviation at the time of the right gaze (Spearman's rank correlation coefficient, 0.251). There was a correlation between deviations when gazing to the left (Spearman's rank correlation coefficient, -0.466; Fig. 5).

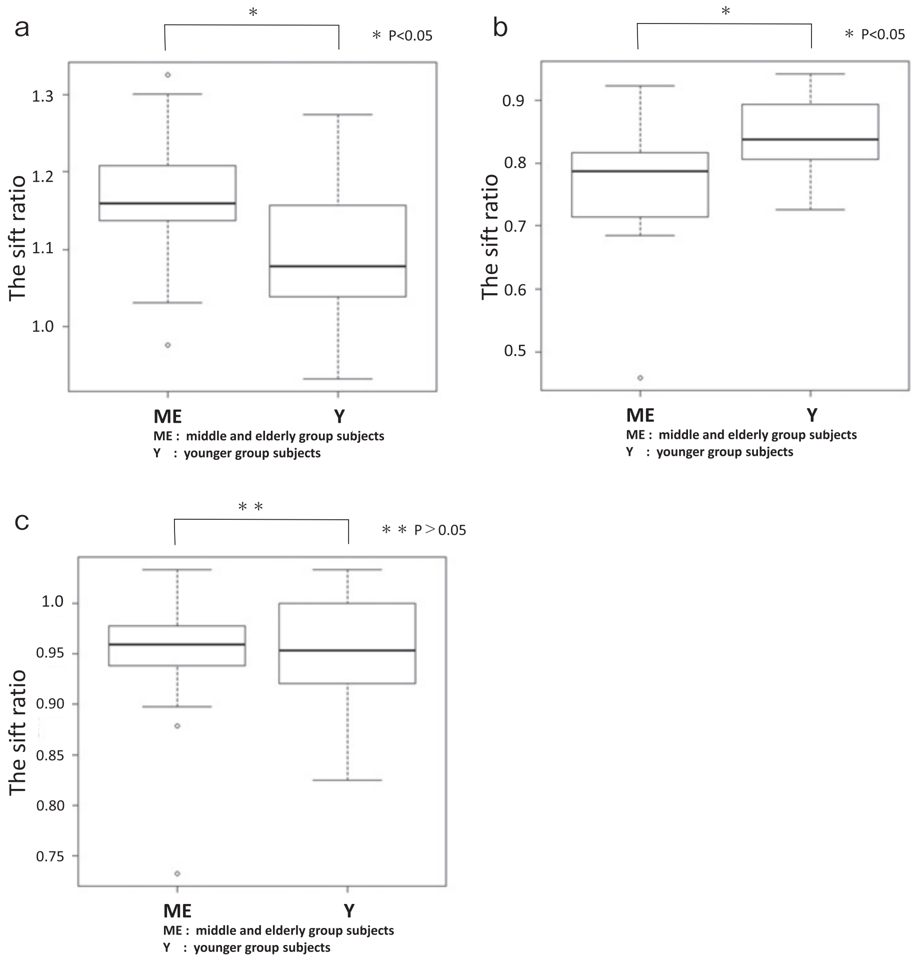

Fig. 4 Comparison of medial axis deviation. (a) Right 30° gaze. (b) Left 30° gaze. (c) 0° gaze.

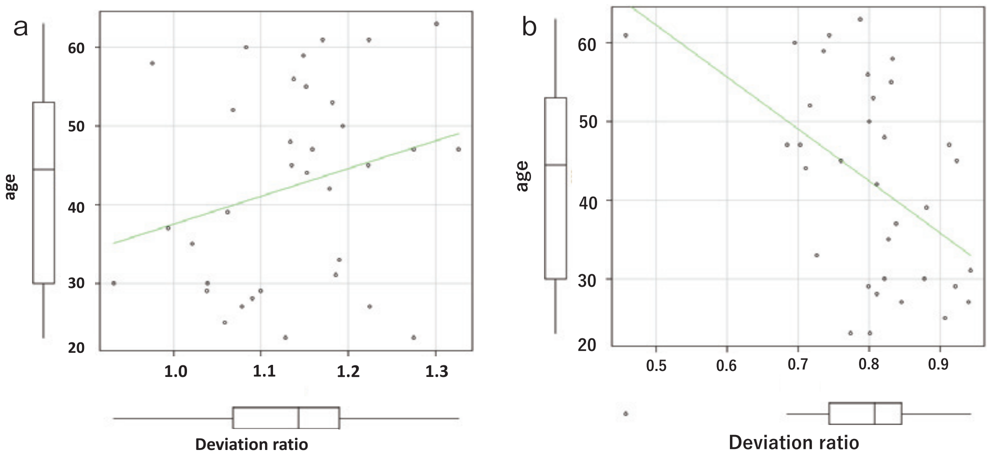

Fig. 5 The correlation between the subject's age and the deviation ratio.
The correlation between the subject's age and deviation ratio was evaluated by Spearman's ordinal correlation coefficient. A weak correlation was found in the deviation at the time of right gaze. There was a correlation between deviations when gazing to the left.
(a) Right 30° gaze. (b) Left 30° gaze.

Discussion

The sense of direction is a binaural hearing phenomenon that is useful for diagnosing retrocochlear deafness.[8] Sound source localization is formed by the difference in sound intensity and time heard from both ears. The direction test used in this study can quantitatively record sound image localization.[4] Adding visual stimulation also enabled us to detect the effects of aging on the young age group and the middle-aged and elderly group. When the subjects gazed at 30° to the left and right, there was a significant difference in the deviation of the medial axis between the middle-aged and elderly group and the young age group. The medial axis of the sense of direction deviated in the gaze direction by lateral gaze, suggesting that the subjective centrosome axis in each subject deviated. Compared with young subjects, middle-aged and elderly subjects tilted their centrosome axis more, which could be due to changes in eye position. Collectively, these results support that eye position has a stronger effect on spatial orientation in middle-aged and elderly individuals.

In this study, it was found that the change in eye position affected the central axis of the self, and the effect was greater in middle-aged and elderly people. Furthermore, it has been reported that changes in eye position significantly affect the central axis of the self when both inner ear vestibular stimulation and changes in eye position are received at the same time.[14] Therefore, especially in middle-aged and elderly people, sudden changes in eye position during body movement are likely to cause imbalance. When there is little spatial information (e.g., moving in a dark place, walking in a muddy place with poor footing, or age-related bilateral vestibular disorders), it should be noted that middle-aged and elderly people lose their balance because of sudden changes in eye position and are at an increased risk of falling.

Otake et al.[15] measured the ITD threshold in 10 subjects (mean age, 25 years) using a device similar to that used in our study. The deviation of the medial axis when the subject gazed 30° to the left and right was measured, and the deviation was in the gaze direction. Lewald et al.[16] measured the discrimination threshold for interaural intensity difference in 13 subjects with a lateral gaze. The sound image localization changed because of lateral gaze, and the medial axis of the discrimination threshold deviated. This phenomenon was also observed in the position of the lateral eye, indicating that it was not the effect of visual-auditory interference but the effect of eye position change-auditory interference. From a neurophysiological viewpoint, Jay et al.[9] conducted monkey experiments to investigate the activity of burst neurons associated with impulsive saccades. The results showed that auditory and visual signals share a common motor circuit in the superior colliculus. Furthermore, the auditory receptive field in the superior colliculus shifted with changes in eye position and allowed the auditory and visual maps to remain in the register.

Retrocochlear sensorineural hearing loss is primarily due to the degeneration and disappearance of cochlear nerve fibers and central relay nucleus cells.[10, 11, 17–19] Sato et al.[4] examined the ITD threshold, which is recorded as the amplitude of sawtooth waves in a sound image test, by age group in 152 subjects aged 10-70 years. The average amplitude was slightly larger among subjects aged 30-50 years than those in their teens to 20 years. Furthermore, subjects aged 60-70 years had greater variance and mean values than did other age groups. This result indicates that the ITD threshold in sound image localization tends to increase with age, and individual differences also increase. Hisamatsu et al.[20] reported the relationship between the sense of direction of sound and aging by comparing it in three groups: young age group (i.e., age <40 years), middle-aged group (i.e., age ≥40 to <60 years), and old age group (i.e., age ≥60 years). There was a significant difference in the ITD threshold for sound image localization between the old age and the young age groups, but not between the young and middle-aged groups. In the current study, the amplitude tended to be greater according to aging, but it was not significantly different. This result may be because of the age distribution between our study and those of previous studies. In our study, the percentage of people in their 60s is 12%. In contrast, in previous studies, 36% were in their 60s or older.

Neural circuit of eye movement and sense of direction

The sound information input from both ears merges at the superior olivary complex and is projected onto the superior colliculus to interfere with visual information.[16] In our study, it was considered that the interference in the superior colliculus region had a stronger effect on the central axis deviation in the middle-aged and elderly group than in the young age group. This could be because the superior colliculus serves as a relay point in both neurotransmission pathways.

The nuclei of cranial nerves III, IV, and VI affect eye movement differently. The lower center connects directly to the extraocular muscle-dominant cranial nerve nucleus and causes horizontal and vertical synkinesis.[21–23] The upper center indirectly controls the extraocular muscles through the lower center. The superior colliculus contains various structures, such as the frontal eye field, occipital lobe, superior colliculus, and posterior parietal cortex.[21–23] It is involved in auditory and somatosensory processing, in addition to converged visual information processing.

Regarding the mechanism of establishing a sense of direction, Van Bergeijk et al.[24] reported that nerve fibers ascending from the cochlear nucleus are divided into two groups. One reaches the contralateral medial superior olivary complex, and the other reaches the ipsilateral medial superior olivary complex. The former is excitatory, whereas the latter is inhibitory. The sense of direction is caused by the difference in the amount of information between the two signals from the medial nucleus of the superior olivary complex to the auditory cortex. Jeffress[25] described a neural circuit that enabled the detection of ITD using a model consisting of a row of simultaneous detector cells and an ear-derived neural projection called a delay-line circuit.

Auditory information is first received as a frequency that is decomposed in the cochlea and then transmitted through the auditory nerve to the cochlear nucleus of the brain stem. The superior olivary complex is the first nerve nucleus to detect ITD in mammals. The information extracted from the medial superior olivary complex is projected onto the lateral lemniscus and inferior colliculus.[26] The cells of the inferior colliculus project nerves to the superior colliculus, which is an important area for visual-spatial localization. A spatial map based on auditory information is also formed in the superior colliculus.[27] The cells of the superior colliculus project signals to the brain stem and spinal cord, affecting spatial information, coordinated eye movements, and head position.

To summarize the discussion in this section, both the information in the eye motor nerve transmission pathway and the auditory information processing pathway use the superior colliculus as a relay point. Therefore, it is presumed that the interference at the superior colliculus level affected the central axis deviation of the sound image localization during lateral gaze.

Sense of direction in artificial hearing device

One of the goals of wearing a hearing aid in both ears is to improve the sense of sound direction. The number of patients wearing artificial hearing devices, such as cochlear implants, has increased in recent years. There are no reports of directional tests due to changes in eye position in cochlear implant wearers, but we describe the differences in directional sense acquisition depending on age of cochlear implant surgery. Binaural hearing function contributes to the sense of direction of the bilateral cochlear implant wearer, but there are many unclear points regarding the ILD and the ITD. Gordon et al.[28] divided 79 children who underwent bilateral CI with sequential and simultaneous surgery into three groups: (1) the group that underwent contralateral surgery after a long period of time after surgery, (2) the group that underwent contralateral surgery after a short period of time after surgery, and (3) the group that underwent concurrent bilateral surgery. ILD was detectable in all groups, but ITD was easier to detect in the group that underwent concurrent bilateral surgery at an early age. In addition, a longer wearing period was also reported to be associated with better performance in the sense of direction among pediatric cochlear implant wearers.[29] Zheng et al.[30] compared the sense of direction under noise and reverberation between adult bilateral cochlear implant wearers and healthy subjects and found an inferior sense of direction in subjects wearing bilateral cochlear implants.

Sense of direction develops from about 4 months and reaches adult levels by age 5 years. Binaural listening experience at a relatively young age influences the development of the sense of direction.[31, 32]

However, the effect of age at the start of wearing or the time to wearing on the benefit of a sense of direction from an artificial hearing device in adults is still unclear. In addition, the influence of changes in head position and gaze on the acquired sense of direction is still unclear.

In this study, it was found that middle-aged and elderly people had a more deviated sense of sound direction due to eye position stimulation than younger people. It is suggested that cochlear implant wearers may also have axial changes depending on their age in situations where eye position stimulation is applied. This may help clarify the age-related spatial cognition of cochlear implant wearers.

Limitations of this study

Regarding the number of subjects in the middle-aged and elderly group, the number of elderly subjects aged 60 years or older was lower. As the theme of this test was to investigate the difference between those under 40 years old and those over 40 years old, I think that the research itself was not a problem. However, if the number of subjects aged 60 and over was larger, the comparison result of the discrimination threshold may have changed. In addition, I think we were able to evaluate by dividing subjects into three groups: young age group, middle-aged group, and old age group.

Conclusion

Eye position interferes more strongly with the sense of direction than does age at which the ITD threshold changes.

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Authors' contribution: T.M. designed the study; collected, analyzed, and interpreted the data; and wrote the manuscript. H.T. supervised the research. M.S., who is the research leader, guided the entire study and made the final approval of the manuscript.

Ethics statement: The study protocol was approved by the Institutional Review Board of Toranomon Hospital (approval number: 2092).

Conflicts of interest: None declared.

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