ARTICLE IN PRESS
JID: ANL [mNS;July 4, 2023;14:19]

Auris Nasus Larynx xxx (xxxx) xxx

Contents lists available at ScienceDirect

Auris Nasus Larynx

journal homepage: www.elsevier.com/locate/anl

A manual of Eustachian tube function tests–illustration of representative test results obtained from healthy subjects and typical disorders with suggestion of the appropriate test method of choice[☆]

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ARTICLE INFO

Article history:
Received 26 April 2023
Accepted 26 June 2023
Available online xxx

Keywords:
Sonotubometry
Otitis media
Tympanic membrane
Silicone plug

ABSTRACT

In the 19th century, Politzer devised a method to measure passage of the Eustachian tube (ET) by pressurizing the nasopharyngeal cavity, which marked the beginning of the ET function test. Since then, various examination methods have been developed. While ET function testing is important, recent advancements in diagnostic imaging and treatments have renewed interest on its importance. In Japan, the main objective methods used for examining ET function include tubotympanoaero-dynamic graphy (TTAG), sonotubometry, and the inflation-deflation test. The Japan Otological Society (JOS) Eustachian Tube Committee has proposed a manual of ET function tests, which presents typical patterns of the normal ear and typical diseases and suggests the ET function test of choice for each disease. However, the diagnosis of each disease should

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https://doi.org/10.1016/j.anl.2023.06.005

be made based on a comprehensive history and various examination findings, with ET function tests playing a supplemental role in the diagnosis.

1. Introduction

As early as in the 19th century, Politzer [1] devised a method to measure passage of the Eustachian tube (ET) by pressurizing the nasopharyngeal cavity with a hand-held air bag, which marked the beginning of the ET function test. Since then, various examination methods have been devised [2–9]. While ET function testing is important [1–12], there has been recent enthusiastic reevaluation of its importance [13–17]. This is mainly due to the advent of new diagnostic imaging of the ET [18–22] and treatment for chronic ET dysfunction, including both stenotic dysfunction and patulous Eustachian tube (PET). The balloon Eustachian tuboplasty (BET) [23–26] is now performed for stenotic dysfunction in many institutions globally, and various treatments have also been introduced for intractable PET [27–29]. The plug surgery using a silicone plug (Kobayashi plug) [17,27,30-34] is now covered by public health insurance in Japan after a prospective, multicenter trial [33].

Today, the main objective methods used in Japan for examining ET function consists of the tubotympanoaero-dynamic graphy (TTAG) [4,5], the sonotubometory [2,3], and the inflation-deflation test [6–8]. The Japan Otological Society (JOS) Eustachian Tube Committee first proposed a manual of ET function tests written in Japanese in 2004. The second edition was published in 2007 and the third edition was proposed in 2016. The manual presents typical patterns of the normal ear and typical diseases and suggests the ET function test of choice for each disease. The manual illustrates the test results obtained by using JK-05A (RION Co., Ltd., Kokubunji, Tokyo, Japan), an all-in-one device marketed since 2008. This paper describes the latest edition of the manual in English to promote access from the international medical community working in the field of clinical otology related to ET function.

However, the diagnosis of each disease should be made based on a comprehensive history and various examination findings [12,28,34]. The ET function tests play a supplemental role in the diagnosis.

2. Tubotympanoaero-dynamic graphy (TTAG) (Fig. 1A, 2A, 3A, 4A, 5A, 8B, 9A) and Impedance method (Fig. 3B)

In 1974, Kumazawa et al. reported a method to detect changes of the middle ear pressure reflected by the pressure change in the external auditory canal (EAC) [4]. The Valsalva maneuver is used to observe whether the middle ear pressure elevates, whether the created positive pressure is released by swallowing (Fig. 1A), and whether the EAC pressure changes in synchronization with nasopharyngeal pressure changes caused by deep breathing and sniffing. When the nasopharyngeal pressure rises to 650 daPa or higher by the Valsalva maneuver, the test can evaluate whether the subject has normal passive ET opening, and this is confirmed when EAC pressure elevation is recorded. After confirming passive opening, it is then possible to test active opening of the ET by having the patient swallow several times. When the created positive pressure is released stepwise, the subject is defined to have active ET opening ability (Fig. 1A, 9A). If no change in the EAC pressure is observed during the Valsalva maneuver despite appropriate nasopharyngeal pressure rises to 650 daPa or higher, ET stenosis is suspected (Fig. 2A). If the EAC pressure changes in synchronization with nasopharyngeal pressure change induced by deep nasal breathing or sniffing, this is a finding of PET (Fig. 3A, 4A, 8B). Fluctuation of the tympanic membrane in PET can also be monitored by impedance method (Fig. 3B). The movement (positional change) of the tympanic membrane is detected by changes in an equivalent volume (compliance). Negative pressure in the EAC caused by sniffing reveals the ET closing failure (sniffing type PET) (Fig. 4A, 8B). The synchronization of nasopharyngeal pressure and ear canal pressure, which change in the inverse direction, suggested the false-positive findings of PET (Fig. 5A).

3. Sonotubometry (Fig. 1B, 2B, 3C, 5B, 9B)

Sonotubometry evaluates ET function using sound transmission through the ET. Politzer is credited for the principle of the test, having first reported the phenomenon of sound transmission via the ET in 1869. Since low frequencies can easily pass through thin tubes due to their acoustical characteristics, low frequencies below 2000 Hz were initially used for loading sounds. However, Virtanen et al. [3] conducted a study of suitable frequencies for loading sounds, and since most physiological noise due to swallowing is in the 1000 to 2000 Hz frequency range, band noise of higher frequency (5250-9310 Hz through a full octave bandpass filter) is adopted as loading sounds.

This manual illustrates the representative test results obtained by using JK-05A (RION Co., Ltd., Kokubunji, Tokyo, Japan). In this equipment, 7 kHz band noise is used as loading (presented) sound in sonotubometry. It is presented using a special speaker-phone with an olive-shaped tip placed at the nostril, and the presented sound pressure level (PSPL) is monitored by a microphone inserted in the EAC. After the PSPL

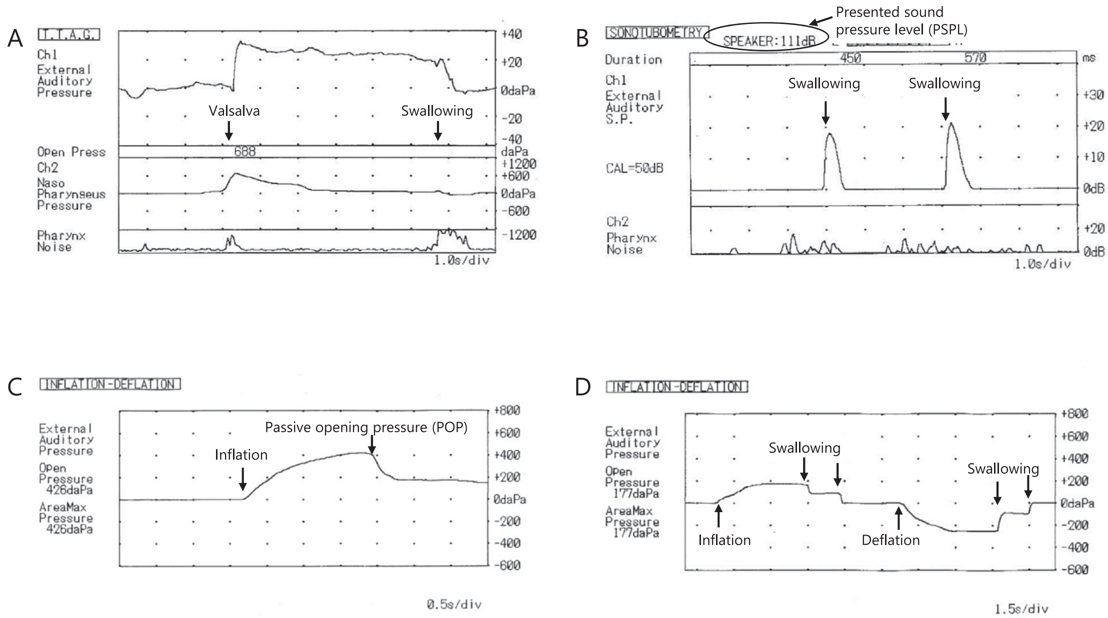

Fig. 1. Typical Patterns of the normal waveform. Even in normal ears, these waveforms are not always obtained. Patulous Eustachian tube (PET) and sniff-type PET may also show normal waveforms. **A. TTAG method** There is an external auditory canal pressure elevation with the Valsalva maneuver (passive opening). Positive pressure is released by swallowing (active opening). **B. Sonotubometry** The ET opens on swallowing and closes within 1 second (active opening). It is important to note that presented sound pressure level (PSPL) exceeds 100 dBSPL, since PET cases may show similar waveform influenced by automatic calibration of the test device. If it is lower than 100dB SPL, PET may be present. **C, D. Inflation-deflation test** This test requires tympanic membrane perforation or a functioning ventilation tube. C: Passive opening pressure (POP) is within normal range (150-550 daPa [8]). D: Applied positive or negative middle pressure is equalized by swallowing, indicating the presence of active ET opening.

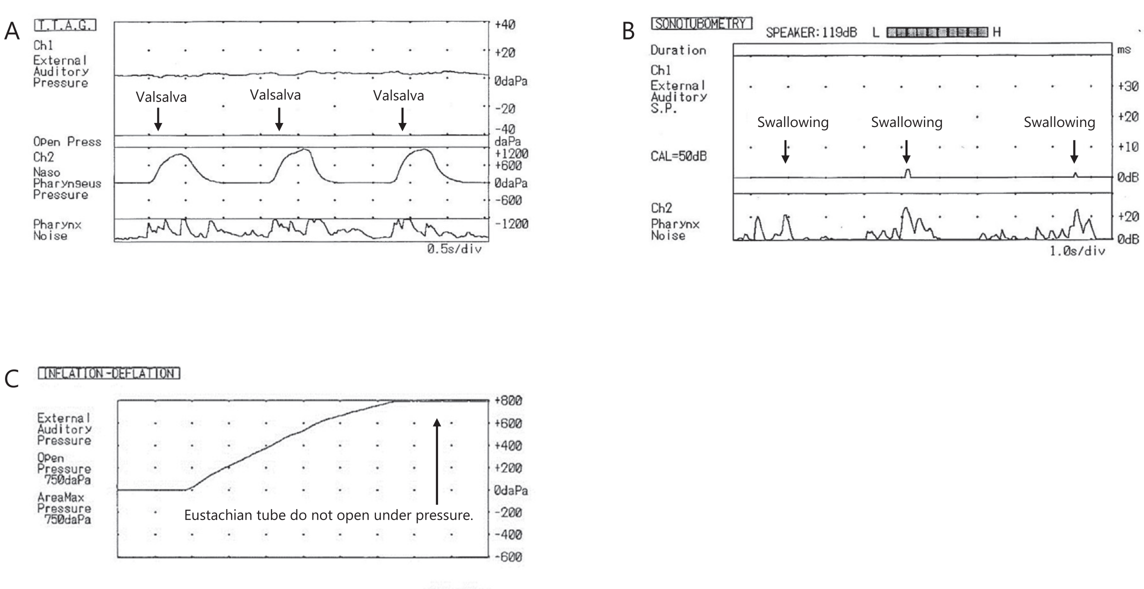

Fig. 2. Typical waveform of stenotic dysfunction of the Eustachian tube. The negative findings of TTAG indicate that the ET does not open during Valsalva maneuver, and sonotubometry indicates absence of active opening during swallowing. However, it cannot be immediately diagnosed as the stenotic dysfunction of ET by these two methods, and inflation deflation test is more reliable to demonstrate poor passage of the ET. **A. TTAG method** The elevation of the nasopharyngeal pressure induced by Valsalva maneuver does not cause an increase ear canal pressure in this case. *Note that nasopharyngeal pressure should exceed 650daPa to confirm that the test has been properly performed. **B. Sonotubometry** There is no EAC sound pressure level increase upon swallowing. *Note that the EAC sound pressure level is greater than 100dBSPL. If it is lower than 100dBSPL, PET may be present. **C. Inflation-deflation test** Inflation-deflation test is the best method for diagnosing ET stenosis. The presence of tympanic membrane perforation or tympanostomy tube is required for the test. When passive opening pressure (POP: normal range 150-550 daPa [8]) is very high, stenotic dysfunction of the ET is suspected. In the case depicted, the ET does not open until the upper limit of pressure measurement (800 daPa), which confirms stenotic dysfunction of the ET.

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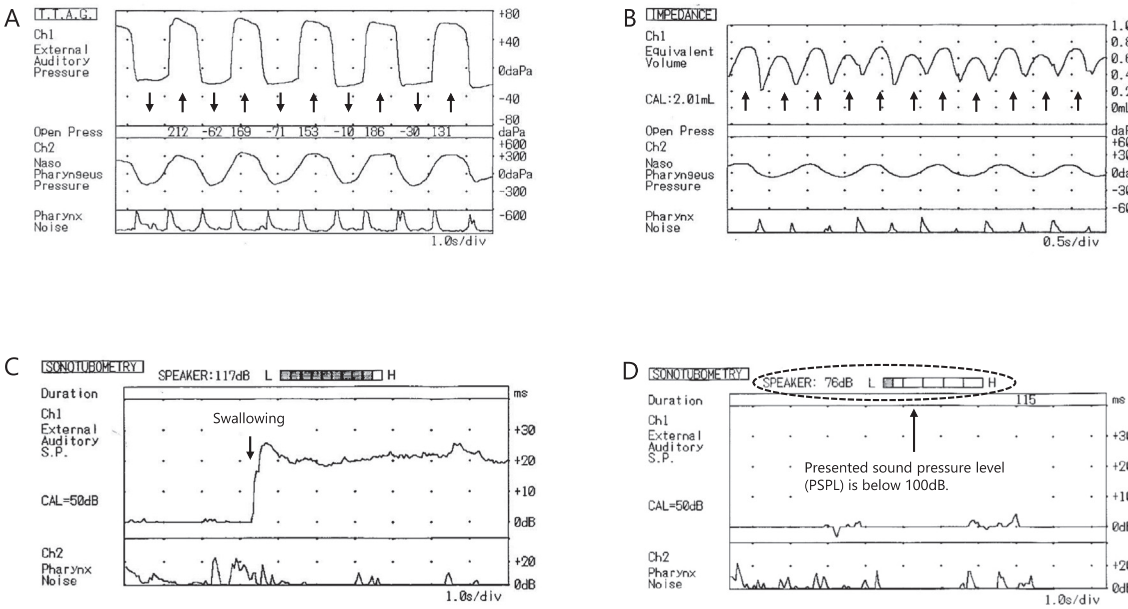

Fig. 3. Typical waveform of Patulous Eustachian tube. **A. TTAG** The external auditory canal pressure fluctuates in synchronization with the nasopharyngeal pressure (positive pressure during expiration; upward arrows, negative pressure during inspiration; downward arrows) [38]. **B. Impedance method** The movement of the tympanic membrane is detected by changes in an equivalent volume (compliance) (upper column). Note that peaks (arrows) are always positive in both inspirations and expirations. **C, D. Sonotubometry** C: Persistent increase in EAC sound pressure level (SPL) caused by opening of the ET with swallowing (Plateau-shaped waveform). D: PSPL is below 100 dB SPL [39]. Do not mistake this as a finding for ET stenosis.

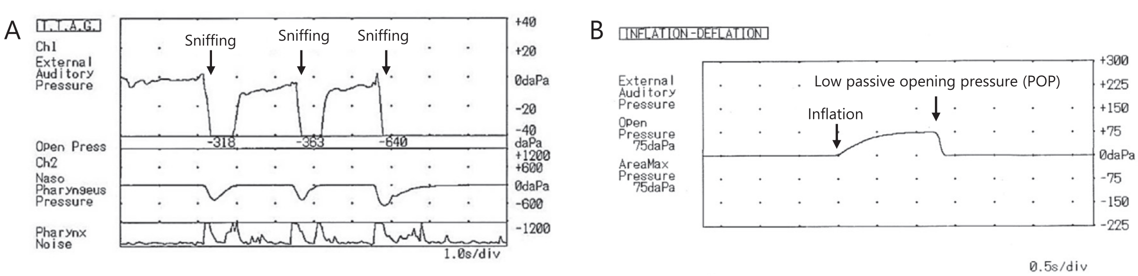

Fig. 4. Typical waveform of Eustachian tube closing failure (sniffing type PET). The ET closing failure is similar to PET [40–47]. It is not always possible to distinguish between these two conditions. The negative pressure formation by sniffing in the TTAG and low POP (<150 daPa) in the inflation-deflation test are also suspicious findings for PET and ET closure failure. **A. TTAG** Sniffing causes negative pressure formation in the EAC. In the presented case the last sniffing locked the ET and negative pressure was maintained thereafter. **B. Inflation-deflation test** Inflation-deflation test can be performed when there is tympanic membrane perforation. The passive opening pressure (POP: normal range 150-550 daPa [8]) is low.

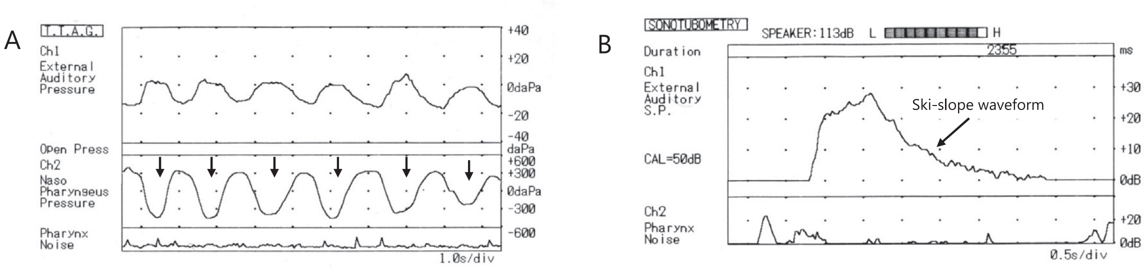

Fig. 5. Tricky waveform (false-positive) in the diagnosis of PET. **A. Inverse phase waveform in TTAG** This case shows synchronization of nasopharyngeal pressure and ear canal pressure; however, the pressure change is in the inverse direction. The mechanism creating the inverse phase waveform may be due to the volume change of the external auditory meatus medial to the ear cuff caused by movement of the jaw or EAC skin accompanied with forced nasal breathing. Arrows indicate the negative nasopharyngeal pressure during inspiration. **B. The ski-slope waveform in sonotubometry** This type of sonotubometry waveform (ski-slope) may sometimes appear in ears with PET. However, it is not correct to diagnose PET solely on this finding since this finding is often seen in normal ears as well.

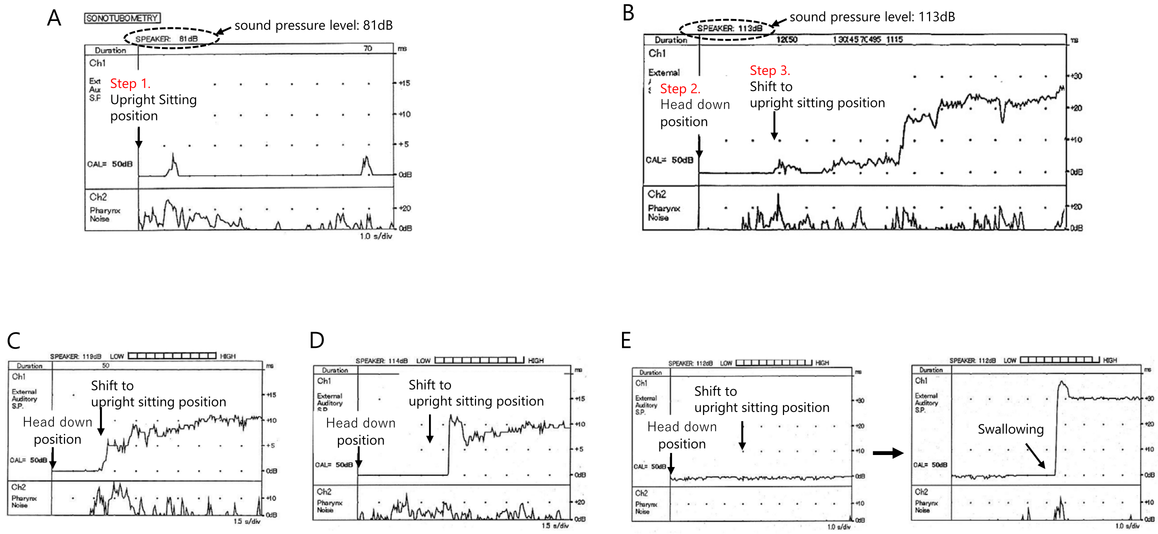

Fig. 6. The diagnosis of the patulous Eustachian tube by the Ohta method [35,36]. **A. Step 1.** Measure the PSPL in the upright sitting position (Check for a lowered PSPL which confirms PET). **B. Step 2. and Step 3.** The PSPL is measured in the head-down sitting position (Check for a PSPL increase in the head-down sitting position and for a difference in PSPL between the head-down and the upright sitting position) (Step 2.). Following this, record the change in EAC SPL while changing body position from the head-down to the upright sitting position (Check for an EAC SPL increase) (Step 3). **Typical waveform (C, D, E)** The degree and manner of ET opening can be interpreted from the pattern of EAC sound pressure level rise during the positional change from a head-down to an upright sitting position. **C. Slow increase waveform** Slow EAC sound pressure level increase indicating slow ET opening. **D. Rapid increase waveform** Rapid EAC sound pressure level increase indicating rapid ET opening. **E. Plateau-shaped waveform after swallowing** In a case without EAC sound pressure level change even after positional change from a head-down to an upright sitting position, the EAC sound pressure level increased rapidly and became stable at a constant value in response to swallowing.

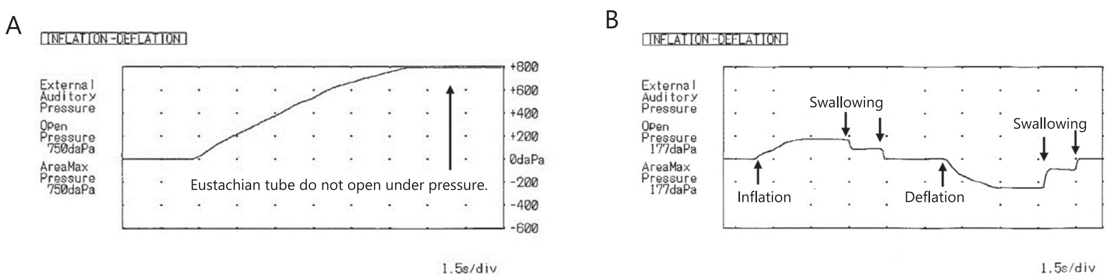

Fig. 7. Preoperative evaluation of Eustachian tube function in chronic otitis media. Both stenotic ET dysfunction and patulous ET may cause problems after surgery for chronic otitis media. If active ET opening is present without findings of PET, the prognosis of middle ear surgery is usually favorable in terms of ET function. **Inflation-deflation test** A. Inflation-deflation test is useful in the diagnosing ET stenosis. In this subject, the passive opening pressure (POP: normal value: 150-550 daPa [8]) was not recorded until 800 daPa indicating ET stenosis. B. Inflation-deflation test can be used to check the active ET opening. In this subject, middle ear pressure (both positive and negative) was equalized by swallowing, demonstrating that active ET opening is present. **Sonotuboomry, TTAG method (figures not shown)** The sonotubometry is used to determine if there is active ET opening, and the TTAG method is used to determine if there is a pattern of ET closing failure (PET with habitual sniffing) (See fig.3). The examination should be performed when otorrhea or middle ear effusion is absent.

is automatically adjusted, the monitored sound pressure level in the EAC is calibrated at a preset level of 50 dB or 55dB (50dB in the present manual). The relative PSPL compared with 50 dB (calibration level) in the EAC is then monitored over time. The ET opening during swallowing (active opening) is evaluated by EAC SPL increase (magnitude in dB) and opening duration (msec) (Fig. 1B, 9B). When there is no active opening during swallowing, stenotic dysfunction of the ET is suspected (Fig. 2B). However, it cannot be immediately diagnosed as the stenotic dysfunction of ET, and inflation deflation test is more reliable to demonstrate poor passage of the ET. When the ET opens while swallowing, the EAC SPL increases steadily, which is a sign of PET (waveform with a plateau shape) (Fig. 3C). The magnitude of PSPL tends to decrease in ears with PET (Fig. 3D) because of the easy transmission of the presented sound through the ET. In some PET cases, a ski-slope waveform may be observed. However, since this finding is frequently observed in healthy ears as well, it is incorrect to diagnose PET solely on this observation (Fig. 5B).

4. Inflation-deflation test (Fig. 1C, 2C, 4B, 7AB, 8A)

Inflation-deflation test is a method to examine ET patency by applying positive and negative pressure to the middle ear cavity from the EAC side. The principle of this method was developed by Flisberg et al [6] as the pressure balance method, and later established by Bluestone et al. [7] by adding the measurement of passive opening and closing pressure. The passive opening pressure (POP, normal value 150-550 daPa

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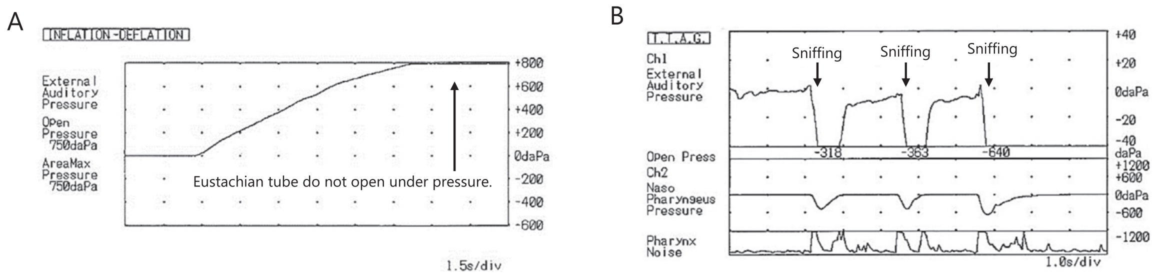

Fig. 8. Prediction of possible refractory cases in the treatment of otitis media with effusion. In ears with otitis media with effusion, both stenotic dysfunction and insufficient closure of the ET can cause refractoriness against treatment. **A. Inflation-deflation test** To improve evaluation accuracy, the test should be performed some time after ventilation tube placement to ensure middle ear effusion in the ET has subsided. By measuring the passive opening pressure (POP: normal value 150-550 daPa [8]), stenosis or PET is diagnosed. **B. TTAG** Unconscious sniffing habit in ears with insufficiently closed ET can cause chronic secretory otitis media. TTAG may show negative pressure formation induced by sniffing in such cases. In the presented case the last sniffing locked the ET and negative pressure was maintained thereafter. In the case with PET, the EAC pressure (or tympanic membrane impedance) may fluctuate synchronously with breathing (figure not shown, see figure 3A, 3B). *There is no precise indication for ventilation tube removal based on ET function alone. However, when the POP is abnormally high, it is highly possible that the prognosis will be bad after ventilation tube removal.

[8]) and the active opening pressure can be determined, but the presence of tympanic membrane perforation, or a ventilation tube is a prerequisite for the examination. The EAC is sealed with an earplug and pressure is recorded with a pressure transducer. A syringe is used to apply pressure to the middle ear between the earplug and the pressure transducer. First, the examiner applies pressure to the ET while the subject is at rest and checks the pressure at which air spontaneously leaks through the ET into the nasopharynx. This is called POP and is an indicator of ET patency (Fig. 1C). Then, a constant positive or negative pressure (usually ±200 daPa) is applied to the middle ear and ET, and the subject is asked to swallow several times to see if the pressure decreases (Fig.1D, 7B). This test is used to determine the active middle ear ventilating or equalizing ability of the ET, i.e., whether the pressure difference between atmospheric pressure and middle ear pressure can be eliminated by active ET opening during swallowing. (The positive pressure test is more important since even normal subjects often lack capability of eliminating negative middle ear pressure). Stenotic dysfunction of the ET is suspected when POP is extremely high (normal range: 150–550 daPa) (Fig. 2C, 7A, 8A). When measuring POP, the pressure should not exceed 850 daPa except under a special setting planned by a medical staff (Fig. 2C). If the patient complains of any physical abnormality (pain, dizziness, etc.) during the examination, the examination should be stopped immediately.

5. Postural change ET function test using sonotubometry (Ohta method) [35,36] (Fig. 6)

Ohta developed an elegant method for PET diagnosis using sonotubometry by performing sequential measurements during body posture change. This method utilizes a PET characteristic whereby the ET closes upon postural change in majority of patients, although there are rare exceptions in which the PET does not close even in the supine position [37].

The procedure of the Ohta method is as follows.

Step 1. Sonotubometry in the upright sitting position. (Fig. 6A)

Step 2. Sonotubometry in the head-down sitting position. (Fig. 6B)

Step 3. Postural changing from the head-down to the upright sitting position. (Fig. 6B)

As described before in the section of sonotubometry, a microphone is inserted into the subject's EAC and a speakerphone with an olive-shaped tip is applied at the subject's ipsilateral nostril. The PSPL introduced into the nasopharynx is first measured, with the subject in the upright sitting position (Step 1). Once the test device is reset, the PSPL is measured with the subject in the head-down sitting position (Step 2) (sitting in a chair with the head between the knees). Finally, the EAC sound pressure level is measured as the subject's posture changes from the head-down to the upright sitting position (Step 3).

If the subject's ET is continuously open (PET), recording Step 1 should exhibit decreased PSPL, but recording Step 2 should have higher PSPL due to ET closure in such a posture. Recording Step 3 should exhibit EAC SPL increase due to ET re-opening from a head-down to an upright sitting position. The degree and manner of ET opening can be interpreted from the three patterns of EAC sound pressure level rise during the positional change from a head-down to an upright sitting position. The slow increase waveform records a slow EAC sound pressure level increase indicating slow ET opening (Fig. 6C). The rapid increase waveform records a rapid EAC sound pressure level increase indicating rapid ET opening (Fig. 6D). In a case without EAC sound pressure level change even after positional change from a head-down to an upright sitting position, the EAC sound pressure level increased rapidly and became stable at a constant value in response to swallowing (Plateau-shaped waveform after swallowing) (Fig. 6E).

In several studies examining postural changes in the ET in patients with PET, the ET lumen has been shown to be wider in the sitting position than in the spine or head-down position on computed tomography [19–22]. The mechanism by which the open ET is closed by taking the spine or head-down sitting position is considered to be attributable to mucosal edema of the ET or tissue compression surrounding the ET (particularly

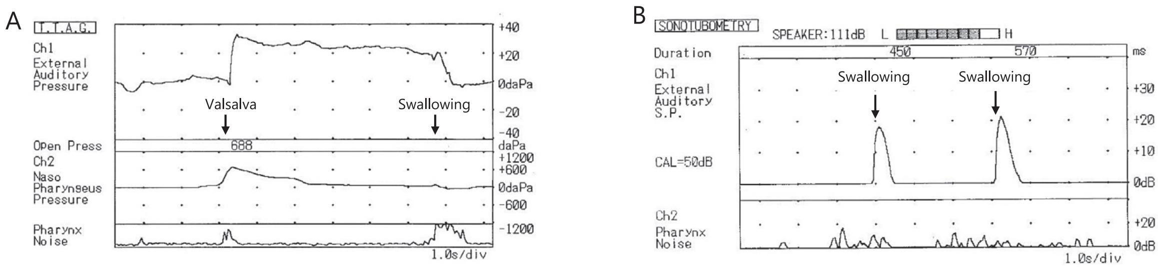

Fig. 9. Testing the adaptability for abnormal pressure environments (scuba diving and aircraft boarding). The minimum requirement is the capability of equalizing middle ear pressure by oneself (Valsalva maneuver). If the active ET opening during swallowing is verified, it is more convincing. *However, it is important to explain to the patient that the ability to perform the Valsalva maneuver does not necessarily guarantee safe diving or flight. **A. TTAG** Test if the ET is opened by the Valsalva maneuver, which is objectively verified by the positive pressure creation in the EAC, followed by the elimination of the pressure by swallowing indicating active ET opening in this case. **B. Sonotubometry** Test if the ET can be opened by swallowing (active opening is verified in the case presented).

the pterygoid plexus) [18]. By applying these mechanisms, the Ota method can detect the opening and closing of the ET in patients with PET by postural changes.

Author Contributions

Contributor TK and HT was responsible for the organization and coordination of the manual. All authors contributed to the writing of the final manuscript. All members of the Eustachian Tube Committee of the Japan Otological Society (JOS) contributed to the management or administration of the manual.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Funding

A portion of this study was supported by Funds from the Japan Otological Society.

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Please cite this article as: R. Ikeda, S. Ohta, S. Yoshioka et al., A manual of Eustachian tube function tests-illustration of representative test results obtained from healthy subjects and typical disorders with suggestion of the appropriate test method of choice, Auris Nasus Larynx, https://doi.org/10.1016/j.anl.2023.06.005