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Dynamic characteristics of the middle ear in neonates

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ABSTRACT

Objective: Early diagnosis and treatment of hearing disorders in neonates is highly effective for realization of linguistic competence and intellectual development. To objectively and quickly evaluate the dynamic characteristics of the middle ear, a sweep frequency impedance (SFI) meter was developed, which allowed the diagnosis of middle-ear dysfunctions in adults and children. However, this SFI meter was not applicable to neonates since the size of the measurement probe was too large. In the present study, therefore, the SFI meter was improved, i.e., the diameter of the probe was reduced to that of the neonatal external ear canal. By using this newly designed SFI meter, SFI tests were performed in healthy neonates.

Methods: A sound of the sweeping sinusoidal frequency between 0.1 kHz and 2.0 kHz in 0.02-kHz step intervals is presented to the ear canal by an SFI probe while the static pressure of the ear canal is kept constant. During this procedure, the sound pressure level (SPL) is measured. The measurements are performed at 50-daPa intervals of static pressure from 200 daPa to −200 daPa.

Results: Measurements were conducted in 10 ears of 9 neonates. The SPL showed two variations at 0.26 ± 0.03 kHz and 1.13 ± 0.12 kHz. Since the SPL is known to show a variation at frequencies from 1.0 kHz to 1.6 kHz due to the resonance of the middle ear in adults and children with normal hearing, the second variation is probably related to such resonance in neonates. The measurement of gel models, which mimics the neonatal external ear canal, showed a variation in SPL at around 0.5 kHz. This implies that the source of the first variation may possibly be related to the resonance of the external ear canal wall.

Conclusions: SFI tests revealed that there were two variations in the SPL curve in neonates, one at 0.26 ± 0.03 kHz and the other at 1.13 ± 0.12 kHz, the former and the latter being possibly related to the resonance of the external ear canal wall and that of the middle ear, respectively. This result suggests that the dynamic characteristics of the middle ear in neonates are different from those in adults.

1. Introduction

Hearing disorders are reported to occur in about 1–2 out of every 1000 neonates [1–6]. Early diagnosis and treatment of such disorders in neonates is highly effective for realization of linguistic competence and the intellectual development [7]. For this reason, it is recommended that infants should be screened for hearing loss before the age of 3 months [8–10]. Current procedures used for hearing screening programs include otoacoustic emissions (OAEs) and automated auditory brainstem response (ABR). Their diagnostic sensitivities have been reported to be high [11,12]. Unfortunately, however, it is impossible to diagnose the type of hearing loss such as conductive hearing loss and sensorineural hearing loss by these methods. Although bone-conduction ABR makes such diagnosis possible, it is not recommended to use for neonatal hearing screening in the guideline published by the joint committee on infant hearing (JCIH), USA [10].

Tympanometry has been generally used for diagnosis of middle ear dysfunction. The probe tone frequency of tympanometry is normally 226 Hz. Conventional 226-Hz tympanometry has been

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acknowledged as a reliable method for detecting middle ear dysfunction in adults and children [13,14]. However, the use of conventional 226-Hz tympanometry has been proven to be inaccurate in the diagnosis of infants younger than 7 months of age [15–18]. For instance, infants who have middle-ear effusion may possibly be regarded as having normal middle ears by conventional tympanometry [17–19]. In addition, conventional tympanometry often shows abnormal middle ears in normal infants [16]. Recently developed tympanometry using a 1000-Hz probe tone has been applied to newborns [20–22] and has been reported to be more sensitive to otitis media with effusion in infants aged less than 7 months than the conventional method [15,23]. The reasons for such inaccuracy of the conventional 226-Hz tympanometry in the diagnosis of infants and higher sensitivity of the 1000-Hz tympanometry remain unknown, although physical differences in the outer and middle ears between infants and adults/children were suggested as a possible reason. Wideband acoustic transfer functions (ATFs), which include energy reflectance and acoustic admittance, have also been reported to be a useful test to identify conductive dysfunction in newborns [24–27]. Although such tympanometry with a high probe tone frequency and wideband ATFs are useful for newborns, knowledge of the dynamic characteristics of the middle ear in neonates is limited.

To objectively and quickly evaluate the dynamic characteristics of the middle ear, a sweep frequency impedance (SFI) meter was developed in the 1990s [28]. It was designed to measure the dynamic characteristics of the middle ear in adults and children [28–32]. This SFI meter utilizes a different approach from multi-frequency tympanometers. That is, it does not measure the admittance of the middle ear, but rather the sound pressure level (SPL) in the ear canal when a stimulus with a frequency varying from 0.1 to 2.0 kHz in 0.02-kHz step intervals is delivered to the ear. At the same time, a constant volume displacement is applied to the ear canal under positive and negative static pressures. In this way, the SFI meter measures the mobility of the middle ear when a sound of the sweeping sinusoidal frequency is delivered into the external ear canal. This mobility reflects rigidities (i.e., Young's moduli) of the middle-ear components, such as the tympanic membrane and the ligaments and tendons of the ossicles. Therefore, if Young's moduli of the middle-ear components become large, their rigidities become large, leading to low mobility of the middle ear. To explain the relationship between the measurement results and the conditions of the middle ear, a theoretical model of the external ear and the middle ear in adults was constructed [29]. This theoretical model makes it possible to accurately diagnose middle ear dysfunctions in adults [30] and also enables the investigation of the mechanical properties of the middle ear, which are difficult to measure experimentally.

Thus, the SFI meter has potential as a diagnostic tool for the middle ear dysfunction in neonates. However, it was not applicable to neonates because of its large probe, and the measurement results have not been obtained from neonates. In the present study, to clarify the middle-ear dynamic characteristics in neonates, a smaller probe designed for neonates was developed. The validity of the improved SFI meter was confirmed by examining the frequency characteristics of the probe using calibration cavities and by performing the SFI test in the normal hearing adults. SFI tests were then performed in healthy neonates.

2. Materials and methods

2.1. Improvement of SFI meter

A schematic diagram of the device is shown in Fig. 1. The SFI device consists of a personal computer (CF-W7, Panasonic, Osaka, Japan), an AD/DA converter (NI 6024E, National Instruments, Austin, TX, USA), a probe system (ER-10C, Etymotic Research, Elk Grove Village, IL, USA), a stepping motor (KR-3ML, Techno Drive, Kawasaki, Japan), an air pump (Custom made, Minato Concept, Tokyo, Japan), a pressure sensor (PA-100-500D-W, Nidec Copal Electronics, Tokyo, Japan), and a pressure relief valve (790 Dual Action Breather Valve, Halkey-Roberts, St. Petersburg, FL, USA). As a system power source, a transformer (AMS150-24, Nagano Japan Radio, Nagano, Japan), which conforms to the general standard IEC 60601-1 [33], was used.

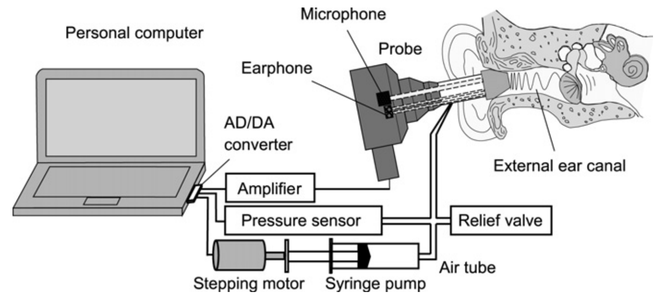

Fig. 1. Schema of the SFI meter for testing neonates. The SFI meter consists of a personal computer, an AD/DA converter, a probe system, a stepping motor, a syringe pump, a pressure sensor and a relief valve. This new SFI meter is controlled using LabView.

To measure the dynamic characteristics of the middle ear in neonates, a new SFI probe was developed. The diameter of the new probe is approximately 3 mm, while that of the conventional probe is approximately 5 mm. There are three holes in this 3-mm probe: Hole 1 applies static pressure P_s, Hole 2 delivers sound to the external ear canal from an earphone and Hole 3 measures sound pressure in the ear canal by a microphone. A specially designed cuff suitable for testing neonates is attached to the tip of the probe to seal off the ear canal during testing.

To examine the frequency characteristics of the newly developed probe, the relationship between the input sound frequency and the SPL measured by the microphone, the so-called SPL curve, was obtained using a calibration cavity, which was made of an air-filled plastic circular cylinder rigidly terminated at one end. The lengths of the calibration cavity l_c were 5, 15, 25 and 35 mm and their diameters were 4 mm.

To theoretically confirm the frequency characteristics mentioned above, numerical results were obtained from the impedance theory of the tube derived from the one-dimensional wave equation. This theory is applicable when the sound wave length is large compared with the tube radius. When the mechanical impedance at the right side of the calibration cavity is defined as $Z = \infty$, the relationship between the sound pressure P in the calibration cavity and the constant volume displacement ΔV of the earphone is given in the form

$$\frac{P}{\Delta V} = \omega \frac{\rho_a u_a \cos \gamma l}{S \sin \gamma l}, \quad (1)$$

where l and S are the length and cross-sectional area of the calibration cavity, $u_a = (K_a/\rho_a)^{1/2}$ is the sound velocity, K_a and ρ_a are the bulk modulus, which indicates a coefficient of elasticity defined by the ratio of a pressure applied to a substance to a fractional volume change produced in the substance, and the density of the air, respectively, $\omega = 2\pi f$ is the angular frequency and $\gamma = \omega/u_a$ is the wave number [34]. For numerical calculations, the values of the air-bulk modulus $K_a = 1.36 \times 10^5$ N/m^2 and air density $\rho_a = 1.18$ kg/m^3 are used.

To confirm the validity of the improved SFI meter, 15 normal hearing adults (13 males, 2 females) were recruited from