Sound pressure distribution within human ear canals: II. Reverse mechanical stimulation^{a)}

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This work is part of a study of the interactions of ear canal (EC) sound with tympanic membrane (TM) surface displacements. In human temporal bones, the ossicles were stimulated mechanically “in reverse” to mimic otoacoustic emissions (OAEs), and the sound field within the ear canal was sampled with 0.5–2 mm spacing near the TM surface and at more distal locations within the EC, including along the longitudinal EC axis. Sound fields were measured with the EC open or occluded. The reverse-driven sound field near the TM had larger and more irregular spatial variations below 10 kHz than with forward sound stimulation, consistent with a significant contribution of nonuniform sound modes. These variations generally did not propagate more than ~4 mm laterally from the TM. Longitudinal sound field variations with the EC open or blocked were consistent with standing-wave patterns in tubes with open or closed ends. Relative contributions of the non-uniform components to the total sound pressure near the TM were largest at EC natural frequencies where the longitudinal component was small. Transverse variations in EC sound pressure can be reduced by reducing longitudinal EC sound pressure variations, e.g., via reducing reflections from occluding earplugs. © 2019 Acoustical Society of America. <https://doi.org/10.1121/1.5094776>

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I. INTRODUCTION

This paper is part of a study of the sound field within the human ear canal (EC) (Part I is [Ravicz et al., 2014](#)) and the relationship between sound pressure near the tympanic membrane (TM) and TM motion ([Cheng et al., 2012](#); [Cheng et al., 2015](#); [Cheng et al., 2019](#)). The distribution of sound pressure within the EC of cadaveric human ears in response to sound entering from the external environment has been described as fairly consistent with that predicted for a uniform tube terminated obliquely by a partly absorbent TM ([Stinson, 1985](#); [Hammershøj and Møller, 1996](#); [Stinson and Daigle, 2005](#); [Ravicz et al., 2014](#)). Motion of the ossicles themselves can also generate EC sound, as in the case of otoacoustic emissions (OAEs); however, the distribution of TM-driven sound pressure near the TM and more distally is not known.

OAEs, though they seem to have no physiologic function, are useful indicators of the state of the cochlea (e.g., [Bonfils and Uziel, 1989](#)) and have been used to probe cochlear function and structure ([Long and Tubis, 1988](#); [Zweig and Shera, 1995](#); [Shera et al., 2002](#)) as well as for clinical screening (e.g., [Bonfils et al., 1988](#); [Smurzynski et al., 1990](#); [Lonsbury-Martin and Martin, 1990](#)). Repeatable and reliable measurement of

OAE levels at different frequencies requires an appreciation of variations in the level of both the eliciting stimulus and the resulting OAE with both frequency and location within the EC to minimize errors and measurement variability ([Dreisbach and Siegel, 2001](#); [Souza et al., 2014](#)). Since OAEs are usually measured with the EC blocked by an eartip, the differences in sound field between the blocked and open EC are also important.

In this paper, we describe the spatial distribution of sound pressures in human cadaver ear canals produced by ossicular motion (reverse mechanical stimulation). In this case, sound is produced by motion of the TM driven by the malleus manubrium, which is long and thin and spans approximately half the TM and therefore produces TM motion that varies spatially and with frequency ([Cheng et al., 2015](#); [Cheng et al., 2019](#)). The resulting sound field at any location in the EC is the sum of (a) plane-wave components that propagate longitudinally along the EC, and (b) nonuniform (transversely varying) evanescent components whose amplitude depends on their generation mechanism. These nonuniform components do not propagate at frequencies below a cutoff frequency that depends on EC dimensions; instead, they decay, and the decay distance depends on frequency relative to the cutoff frequency ([Keefe and Benade, 1981](#); [Fletcher, 1992](#)). The longitudinal sound field is determined by reflections from the EC termination that can form standing-wave patterns with local maxima and minima, whereas the nonpropagating nonuniform sound field near the TM is independent of the EC termination. The relative contribution of nonuniform components at a given location is expected to depend on the proximity to their source and the contribution of the plane-wave component;

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for instance, at EC natural frequencies where the plane-wave sound pressure near the TM is minimal, the relative contribution of nonuniform modes to the total sound pressure there should be largest.

We measured sound pressure in nearly intact natural ECs at multiple locations, including (A) across the roughly conical TM within 0.5–1 mm of the TM surface, (B) in a transverse plane perpendicular to the EC axis that intersects the plane of the tympanic ring at the posterior edge, and (C) longitudinally approximately along the EC axis. Sound pressure was measured with the lateral end of the EC open or blocked with a rigid termination. The longitudinal EC measurements describe spatial variations in plane-wave sound pressure and provide a means to estimate the relative contributions of uniform and nonuniform modes to the sound field. We observed that sound varies across the TM at moderate and high frequencies and that the variations are largest at frequencies where the sound pressure near the umbo is a minimum. The results in this paper contribute substantially to knowledge of EC sound fields induced by motions of the TM.

II. METHODS

A. Preparation

This study used two of the four human temporal bones described in the previous paper in this series, TB12 (male, left ear, 73 years) and TB13 (male, right, 67 years), and an additional bone (TB9: female, left ear, 81 years) extracted at autopsy and prepared as described previously (Ravicz *et al.*, 2014). In TB9, the incudostapedial joint had become disarticulated and was repaired with glue.¹ The natural bony ear canal was shortened to allow better access to the medial EC with the microphone probe tube (described below), and a brass sealing ring was glued around the EC opening to allow the opening to be blocked [Fig. 1(A); see also Fig. 1 of Ravicz *et al.*, 2014]. Even though the EC was shortened, we will continue to refer to it as a “natural EC.” The lengths of the shortened canals were TB9, 16.6 mm; TB12, 17 mm; TB13, 13 mm.

The middle ear (ME) was opened at the facial recess to provide visual access to the stapes, and an atticotomy was performed for access to the incus body (Cheng *et al.*, 2012; Cheng *et al.*, 2019).

B. Mechanical stimulation

Mechanical stimuli were delivered with a small actuator that included a piezoelectric stack (PI 882.51, Karlsruhe, Germany; $3 \times 2 \times 18$ mm long) with a tubular extension [18 gauge stainless steel hypodermic tubing: 1.3 mm outer diameter (o.d.) $\times$ 0.8 mm inner diameter (i.d.) $\times$ 17 mm length], see Fig. 1. The actuator was mounted on a polyethylene rod and introduced through the atticotomy into contact with the incus body to stimulate the ossicular chain mechanically (Cheng *et al.*, 2019; see Fig. 1). Broadband chirp stimuli (49 Hz–25 kHz) were synthesized with custom software, attenuated to the desired level (usually 0.1–1 V peak-to-peak; PA5, Tucker-Davis Technologies, Alachua, FL), and

FIG. 1. (Color online) (A) Coronal cross-section of a temporal bone and shortened natural bony ear canal (right ear, anterior view) showing the experimental setup and stimulus and measurement equipment. The middle-ear cavity was opened, and a piezoelectric actuator was placed in contact with the incus via an opening in the ceiling of the ME cavity (an atticotomy). Sound pressure was measured at various locations within the EC: across the TM within 1 mm of the TM surface (P_{TM}), including near the umbo (P_U), and in a transverse plane orthogonal to the EC axis near the superior edge of the tympanic ring (P_{EC}). (B) View medially down the ear canal toward the TM. In each ear, the EC wall limited measurement locations at the TM surface to a subset of the spatial sampling shown as dots. (C) Sound pressure was also measured at locations along the EC axis (P_Z), here shown with the ear canal blocked with a sliding transparent cover that allowed the microphone probe tube to reach all parts of the EC. All sound pressures (P_{TM} , P_U , P_{EC} , P_Z) were measured both with the ear canal open and with it blocked.

sent through an amplifier (D45; Crown Audio, Elkhart IN) to the actuator.

C. Measurement of ear-canal sound field

Sound pressures within the ear canal [80–100 dB sound pressure level (SPL)] resulting from mechanical stimuli were measured with a microphone (Knowles EK23027) and probe tube (0.8 mm o.d., 0.5 mm i.d., 45 mm long). The microphone was glued to a rod mounted in a three-axis micromanipulator (MM33, Märzhäuser, Wetzlar, Germany) so it could be positioned repeatably (with 0.1 mm resolution) at various locations within the EC as described previously (Ravicz *et al.*, 2014).

The sound field² was sampled in several regions: (A) Across the TM within 1 mm of the TM surface (P_{TM}) with 0.5–1 mm spacing [Fig. 1(A)]. The dots in Fig. 1(B) describe spatial sampling at the TM surface. (B) In a transverse plane orthogonal to the EC axis (P_{EC}) with a coarser 2-mm spacing. The transverse plane was near the tympanic ring at the superior edge of the EC and approximately 4 mm from the EC vertex (where the ear canal first meets the TM) at the inferior edge [Fig. 1(A)]. (C) Along the EC axis (P_Z) at 2-mm intervals [Fig. 1(C)]. In the following figures, the measured sound pressure has been normalized to compensate for

the frequency response of the stimulation system and microphone as described below.

D. Measurement technique

The measurement technique, precision, validity checks, and transformation of measurement locations into an anatomy-based coordinate system were identical to those described and used previously (Ravicz *et al.*, 2014). Custom experimental control software (Hi-freq meas system, Eaton-Peabody Lab., Boston, MA) written in LABVIEW on a PXI system (National Instruments, Austin, TX) synthesized stimuli, controlled the attenuator, averaged microphone responses synchronously with the stimulus, and saved data files. Data were analyzed using MATLAB (MathWorks, Natick, MA).

The temporal bone was moistened with saline just before the start of measurements. Measurements took 40–60 min. If measurements were not completed after ~45 min, the bone was moistened again. For some measurements, the lateral end of the EC was blocked with a transparent acrylic cover that included a hole for the probe tube [Fig. 1(C)]. The window was sealed to the brass ring with distilled water. The hole around the probe tube was sealed with moistened cotton. These two movable seals allowed free longitudinal and transverse motion of the probe tube within the ear canal.

E. Checks of measurement validity

The possible sources of measurement error included: (a) sound pressure leaks between the sealing ring and bone or between the cover and the sealing ring or probe tube (for EC blocked measurements); (b) a change in the sensitivity of the probe tube microphone, most likely from the probe tube becoming plugged with fluid or loose tissue; (c) a change in the mechanical stimulation level from a change in the drive or a loosening of the coupling between the actuator and the incus; and (d) a change in TM stiffness due to drying. In addition, (e) low sound levels resulted in microphone responses near its noise floor, generally below about 500 Hz. Any low-frequency sound pressures within 6 dB of the no-stimulus noise floor are omitted from our analyses and later figures.

Our experience allowed us to identify the sources of error as they occurred. When the sealing ring and sliding cover are properly sealed, the sound pressures at low frequencies are generally spatially uniform and vary little between frequencies. A sound pressure leak causes a spatially localized low-frequency pressure-magnitude decrease that disappears above some cutoff frequency. A plugged probe tube manifests itself as a large pressure decrease across frequency in consecutive measurements, greater at high frequencies than lows. Any measurement that showed evidence of either of these problems was repeated after the problem had been corrected.

Changes in sound pressure due to TM drying or changes in actuator coupling (Cheng *et al.*, 2019) were monitored by remeasuring several locations throughout a measurement session (~45 min). For the most part, these measurements were repeatable within 1–2 dB, which indicates that changes in the sound field due to drying were negligible. In bone

TB13, sound pressure near the TM in a narrow frequency band around 7.9 kHz changed at some locations between early measurements and later measurements after remoistening. For this reason, TM sound pressures in this bone are omitted between 7 and 9 kHz.

III. RESULTS

A. Sound pressure distribution maps over the TM in natural ear canals

As described previously (Ravicz *et al.*, 2014), maps of $\hat{P}_{TM}$ variations in the three bones were constructed from the sound pressure responses to broadband stimuli measured near the TM surface. As P_{TM} varies with frequency at all locations due to the frequency response of the actuator and EC, we compute $\hat{P}_{TM}$ as P_{TM} at each location normalized by the sound pressure at the umbo P_U ,

$$\hat{P}_{TM} = P_{TM}/P_U. \quad (1)$$

Maps of the $\hat{P}_{TM}$ distribution in ear TB13 are shown at four example frequencies (6.3, 9.9, 12.2, and 15.8 kHz) in Figs. 2(A)–2(D), and maps of the $\hat{P}_{TM}$ distribution in ears TB9 and TB12 at 9.9 and 12.2 kHz are shown in Figs. 2(E), 2(F) and 2(G), 2(H), respectively. Each map shows a face view of the TM from the ear canal as in Fig. 1(B) and has been rotated so the manubrium is at 12 o'clock. Maps from left ears (TB9 and TB12) are shown mirror-image to be consistent with the map from a right ear (TB13). Each colored (non-gray) square represents a measurement location, and the size of the square is approximately equal to the microphone receptive field (0.5 mm diam.). The location of the umbo is marked with a cross, and the manubrium is outlined in white. The values of $\hat{P}_{TM}$ magnitude $|\hat{P}_{TM}|$ and phase $\angle \hat{P}_{TM}$ are coded by color. The top panels show $\hat{P}_{TM}$ in dB; the bottom panels show $\angle \hat{P}_{TM}$ in cycles. Figure 2 shows that we were able to achieve fairly complete coverage of nearly the entire TM surface in TB13 and a large part of the TM in TB9 and TB12. (Access to the TM in TB9 and TB12 was limited by the shape of the EC.) Video files showing $\hat{P}_{TM}$ maps at all frequencies in all three bones are available in supplementary materials.³

The maps of Fig. 2 show that at some low and high frequencies (e.g., 6.3 and 15.8 kHz in TB13, 12.2 kHz in TB9 and TB12), the measured $\hat{P}_{TM}$ magnitude and phase angle are nearly uniform over most of the TM [$\hat{P}_{TM}$ is ± 3 dB; Figs. 2(A), 2(D), 2(F), 2(H)], where the variations are consistent with small $\hat{P}_{TM}$ magnitude and phase gradients across the TM. At other frequencies (e.g., 9.9 kHz in all bones, 12.2 kHz in TB13), $|\hat{P}_{TM}|$ varies by up to 30 dB and $\angle \hat{P}_{TM}$ varies over 1/2 cycle, with large variations in small regions of 1–3 measurement locations [Figs. 2(B), 2(C), 2(E), 2(G)]. These variations are present in several contiguous frequencies (seen best in the supplementary materials). The presence of these variations is consistent with the existence of modal non-uniformities in the sound field in the transverse plane near the TM (e.g., Rabbitt and Friedrich, 1991); see further discussion in Sec. IV A below. At higher frequencies, $\hat{P}_{TM}$

FIG. 2. Sound pressure maps of the magnitude (top panels) and phase angle (bottom panels) of $\hat{P}_{TM}$ [the sound pressure near the TM surface normalized by that at the umbo P_U ; see Eq. (1)] at representative frequencies. Ear TB13 (right ear): (A) 6.3 kHz, (B) 9.9 kHz, (C) 12.2 kHz, and (D) 15.8 kHz; (E) and (F) ear TB9 (left ear, mirror-image); (G) and (H) TB12 (left ear, mirror-image), 9.9 and 12.2 kHz, respectively. The view is down the EC as in Fig. 1(B) but rotated to orient the lateral process of the manubrium at 12 o'clock (supero-lateral). The umbo is marked by "+," and the manubrium is outlined in white. The ear canal is at 60° postero-superior to the umbo (A), where the projection of the EC axis on the TM is shown by the black dot-dashed line. Each non-gray square denotes a measurement location of size approximately equal to the microphone receptive field (~ 0.5 mm diameter). The gray background is about 8 mm in diameter and approximates the TM. Color scales at right.

varies relatively slowly with frequency over a wider spatial extent, shown more specifically below.

B. Descriptions of transverse sound pressure distributions

To aid in comparing sound pressure distributions among different frequencies and ears, we explore several ways to describe $\hat{P}_{TM}$ variations with location or frequency.

1. Mean P_{TM} in TM quadrants

The complex mean⁴ of $\hat{P}_{TM}$ in each TM quadrant: anterior-inferior (AI) and superior (AS), and posterior

inferior and superior (PI and PS, respectively), was computed and is shown in Fig. 3 (magnitude and phase) as a function of frequency. Because measurements in TB9 and TB12 each covered only part of the TM but the parts were complementary (Fig. 2), we combined $\hat{P}_{TM}$ data for TB9 and TB12 and show quadrant means of the combination in panel (A) to compare with TB13 in panel (B).

The complex means of $\hat{P}_{TM}$ in each quadrant show some frequency and spatial dependence that was common among ears. The mean $|\hat{P}_{TM}|$ and especially the mean $\angle \hat{P}_{TM}$ were fairly uniform among quadrants over low frequency ranges but showed regular differences in higher frequency ranges. At frequencies below 5–7 kHz, the mean $|\hat{P}_{TM}|$ was

FIG. 3. (Color online) Complex mean $\hat{P}_{TM}$ over all measurement locations in each TM quadrant: anterior superior (dotted), anterior inferior (solid), posterior superior (dashed), and posterior inferior (dotted-long-dashed) in (A) the combination of TB9 and TB12, (B) TB13 (data 7–9 kHz omitted—see text). Top panels: magnitude; bottom: phase.

between -3 and $+3$ dB ($\hat{\mathbf{P}}_{\text{TM}}$ within ± 3 dB of $\mathbf{P}_U$) and the mean $\angle \hat{\mathbf{P}}_{\text{TM}}$ was near 0 ($\angle \mathbf{P}_{\text{TM}} \approx \angle \mathbf{P}_U$), except that the combination of ears TB9 and TB12 (“TB9–12”) showed larger variations within narrow frequency ranges near 2.1 and 4 kHz. Between 7 and 10 kHz the mean $\hat{\mathbf{P}}_{\text{TM}}$ in TB9–12 showed large variations between quadrants [Fig. 3(B) does not include the 7–9 kHz range as described in Sec. II E above]. Above 10 kHz the mean $\hat{\mathbf{P}}_{\text{TM}}$ in all ears shows anterior-posterior magnitude and phase variations in some frequency ranges. Above 10 kHz, the mean $\angle \hat{\mathbf{P}}_{\text{TM}}$ in posterior quadrants lagged the mean $\angle \hat{\mathbf{P}}_{\text{TM}}$ in anterior quadrants at all frequencies in TB13 and in several frequency ranges in TB9–12. This observation is consistent with the sound field near the TM including a transverse component in which the anterior $\mathbf{P}_{\text{TM}}$ is approximately 1/2 cycle out of phase with the posterior $\mathbf{P}_{\text{TM}}$.

2. Sound pressure range across the TM and in the transverse EC plane

Additional insights can be gained from plots of the ranges of sound pressure magnitude and phase among measurements over the TM surface or in other measurement planes at all frequencies (as in Ravicz *et al.*, 2014). The ranges of $\hat{\mathbf{P}}_{\text{TM}}$ magnitude and phase [maxima and minima relative to $\mathbf{P}_U$; Eq. (1)] are shown for the three ears by the light-shaded areas in Fig. 4. The range of $|\hat{\mathbf{P}}_{\text{TM}}|$ in all ears (top panels) is consistent with Fig. 2: $|\hat{\mathbf{P}}_{\text{TM}}|$ varies by less than 3–5 dB below 5–8 kHz (except for larger narrowband variations in TB9), $\mathbf{P}_{\text{TM}}$ can be 20–30 dB higher or lower than $\mathbf{P}_U$ in narrow frequency ranges between 6–12 kHz, and $|\hat{\mathbf{P}}_{\text{TM}}|$ ranges between -10 and $+10$ dB up to 16 kHz. It is noteworthy that, in narrow frequency ranges (including those indicated by arrows in Fig. 4), the minimum $|\hat{\mathbf{P}}_{\text{TM}}|$ is near 0 dB, which implies that sound pressure is (nearly) minimum at the umbo.

The ranges of $\hat{\mathbf{P}}_{\text{TM}}$ phase relative to the umbo are shown in the bottom panels in Fig. 4. Generally, frequency regions with large $|\hat{\mathbf{P}}_{\text{TM}}|$ range have wide ranges of $\angle \hat{\mathbf{P}}_{\text{TM}}$ (e.g., 6–10 kHz and above 16 kHz), and frequency ranges in which $|\hat{\mathbf{P}}_{\text{TM}}|$ range is small have a small $\angle \hat{\mathbf{P}}_{\text{TM}}$ range. (Note that we have not attempted to unwrap $\angle \hat{\mathbf{P}}_{\text{TM}}$.) $\angle \hat{\mathbf{P}}_{\text{TM}}$ variations

are both positive and negative, and the $\angle \hat{\mathbf{P}}_{\text{TM}}$ range is nearly -0.5 to $+0.5$ cycles in the 6–10 kHz range, which indicates that the sound pressures over portions of the TM are out of phase with that at the umbo.

We also compute $\hat{\mathbf{P}}_{\text{EC}}$ as the sound pressure $\mathbf{P}_{\text{EC}}$ measured at various locations in a transverse EC plane ~ 4 mm from the umbo and the EC vertex [the most medial part of the EC near the antero-inferior TM, see Fig. 1(A)], normalized by the sound pressure at the EC axis in this plane,

$$\hat{\mathbf{P}}_{\text{EC}} = \mathbf{P}_{\text{EC}} / (\mathbf{P}_{\text{EC}} \text{ on EC axis}). \quad (2)$$

Figure 4 also shows that $\hat{\mathbf{P}}_{\text{EC}}$ is nearly uniform over the measurement locations at nearly all frequencies measured: the range is small below 16 kHz (within ± 3 dB and ± 0.06 cycles in TB9 and TB13, ± 5 dB in TB12) except for isolated frequencies corresponding to $|\hat{\mathbf{P}}_{\text{TM}}|$ extrema. The $\hat{\mathbf{P}}_{\text{EC}}$ range is much larger at higher frequencies. At nearly all frequencies below 16 kHz, the range in $\hat{\mathbf{P}}_{\text{EC}}$ is significantly smaller than the range of $\hat{\mathbf{P}}_{\text{TM}}$ variations. As discussed in Sec. IV A below, the smaller $\hat{\mathbf{P}}_{\text{EC}}$ range is consistent with transverse variations in $\hat{\mathbf{P}}_{\text{TM}}$ diminishing in importance by ~ 4 mm lateral to the TM.

3. Sound pressure phase distribution across TM and transverse EC plane

Though Fig. 4 shows the ranges of $\angle \hat{\mathbf{P}}_{\text{TM}}$ and $\angle \hat{\mathbf{P}}_{\text{EC}}$ variations within the measurement planes, it does not describe the phase distribution. Figure 5 shows the percentage of the $\mathbf{P}_{\text{TM}}$ and $\mathbf{P}_{\text{EC}}$ measurement locations at each frequency for which $\mathbf{P}_{\text{TM}}$ or $\mathbf{P}_{\text{EC}}$ is in-phase or out-of-phase with the reference sound pressure [at the umbo for $\mathbf{P}_{\text{TM}}$ or the center of the EC plane for $\mathbf{P}_{\text{EC}}$; Eq. (1) or (2)]. We define $\angle \hat{\mathbf{P}}_{\text{TM}}$ and $\angle \hat{\mathbf{P}}_{\text{EC}}$ in-phase as $-0.125 < \angle \hat{\mathbf{P}} < +0.125$ cycle and $\angle \hat{\mathbf{P}}$ out-of-phase as $-0.5 \leq \angle \hat{\mathbf{P}} < -0.375$ or $+0.375 < \angle \hat{\mathbf{P}} \leq +0.5$ cycle. (For clarity, the percentage of $\mathbf{P}_{\text{TM}}$ locations in quadrature⁵ is not shown; it can be computed easily as 100% minus the sum of in-phase and out-of-phase percentages.)

At frequencies where the range of $\angle \hat{\mathbf{P}}_{\text{TM}}$ is large in Fig. 4 (e.g., 2–4 and 9–11 kHz in TB9 and 6–10 kHz in TB12), $\hat{\mathbf{P}}_{\text{TM}}$

FIG. 4. (Color online) The ranges of $\hat{\mathbf{P}}_{\text{TM}}$ (light shading) and $\hat{\mathbf{P}}_{\text{EC}}$ [computed by Eq. (2); dark shading] over all measurement locations in (A) TB9, (B) TB12, (C) TB13 (data 7–9 kHz omitted—see text). Black arrows point out frequencies associated with a $|\hat{\mathbf{P}}_{\text{TM}}|$ maxima at which the minimum $|\hat{\mathbf{P}}_{\text{TM}}|$ is near 0 dB. Top panels: magnitude; bottom: phase.

FIG. 5. (Color online) Percentage of measurement locations at which $\angle \hat{P}_{TM}$ (light) and $\angle \hat{P}_{EC}$ (dark) were in-phase (solid lines) or out of phase (dotted or long-dotted-dashed lines)—sound pressure in-phase or out-of-phase with sound pressure over the umbo ($\hat{P}_{TM}$) or at the EC center ($\hat{P}_{EC}$). In-phase is defined as $-0.125 < \angle \hat{P} < +0.125$ cycle; out-of-phase as $-0.5 \leq \angle \hat{P} < -0.375$ or $+0.375 < \angle \hat{P} \leq +0.5$ cycle. Quadrature (other $\angle \hat{P}$) not shown. (A) TB9, (B) TB12, (C) TB13.

is in-phase at fewer than half of the measurement locations (Fig. 5). The smallest percentage of $\angle \hat{P}_{TM}$ in-phase occurs at frequencies at which the $|\hat{P}_{TM}|$ range is large and the minimum $|\hat{P}_{TM}|$ is near 0 dB (e.g., 9.2 kHz in TB9 and 7.5 kHz in TB12). At other frequencies below 16 kHz where the range of $|\hat{P}_{TM}|$ and $\angle \hat{P}_{TM}$ is small in Fig. 4 (e.g., 1–6 kHz, 12–16 kHz), $\angle \hat{P}_{TM}$ is in-phase at nearly all locations. Above 16 kHz, $\angle \hat{P}_{TM}$ is in-phase at about half of the locations and in quadrature at most of the others. This relatively high percentage of locations not in-phase is consistent with the robust anterior-posterior variation shown in Fig. 3.

Figure 5 also includes the $\angle \hat{P}_{EC}$ distribution. Consistent with the small $|\hat{P}_{EC}|$ and $\angle \hat{P}_{EC}$ ranges (Fig. 4), $\angle \hat{P}_{EC}$ is in-phase with the sound pressure at the EC center at nearly all locations at nearly all frequencies.

C. Longitudinal sound pressure variations

Sound pressure was also measured longitudinally approximately along the EC axis (P_Z) from 1 to 2 mm from the umbo to the EC opening. We define $\hat{P}_Z$ similarly to other quantities as the ratio of these measurements to P_U ,

$$\hat{P}_Z = P_Z/P_U. \quad (3)$$

$\hat{P}_Z$ is plotted for each ear in Fig. 6. The longitudinal $\hat{P}_Z$ distribution at a given frequency⁶ can be seen by reading vertically at that frequency.

Large $\hat{P}_Z$ variations between longitudinal locations were seen in all three ears (Fig. 6). Variations at frequencies above 8 kHz were substantially larger in ears TB9 and TB12 (± 20 –30 dB) than in ear TB13. $\hat{P}_Z$ in all ears has several features in common:

- (1) At frequencies below a $|\hat{P}_Z|$ maximum near 8–11 kHz, $|\hat{P}_Z|$ decreases monotonically from measurement locations near the TM to more lateral locations, and $\angle \hat{P}_Z$ is virtually constant and near 0 at all locations, consistent with sound measurements along a short open tube. There are smaller local $\hat{P}_Z$ extrema (maxima or minima) near 3 and 4 kHz in TB9 and near 5 kHz in TB13 that are generally larger at more distal P_Z locations.
- (2) $\hat{P}_Z$ in all ears at all measurement locations shows a magnitude maximum and 0.5-cycle phase change near 9–11 kHz. Because $\hat{P}_Z$ is the ratio of P_Z to P_U , this $|\hat{P}_Z|$ maximum independent of location z is indicative of a sound pressure minimum at the umbo. Its frequency is roughly consistent with the half-wavelength plane-wave resonance in an open tube of the same length as the EC (plus an end correction; e.g., Beranek, 1986; Kinsler

FIG. 6. (Color online) $\hat{P}_Z$ [computed by Eq. (3)] plotted vs frequency at several longitudinal EC locations between the umbo and the EC opening. EC lengths: TB9 (A) and TB12 (B) ~ 17 mm, TB13 (C) ~ 13 mm; hence, no 14-mm curve is available for TB13. Top panels: magnitude; bottom: phase. $\angle \hat{P}_Z$ in TB9 (A) was probably contaminated by noise in $\angle P_U$ at the umbo due to low sound pressure at the node at 9 kHz there; hence, $\angle \hat{P}_Z$ is discontinuous and unwrapped to make $\angle \hat{P}_Z \leq 0$; similarly for $\angle \hat{P}_Z$ in TB12 (B) near 8 and 20 kHz.

et al., 1999), at which frequency the impedance looking through the tube out the open end is very low and the low $|\mathbf{P}_U|$ represents a standing-wave node. The higher frequency of the maximum (11 kHz) in TB13 is consistent with the shorter EC length. The height of this $|\hat{\mathbf{P}}_Z|$ maximum (corresponding to the depth of the umbo pressure minimum) is much greater in TB9 and TB12 (25 and 15 dB, respectively) and the $\angle \hat{\mathbf{P}}_Z$ transition is steeper than in TB13. At the frequency of the $|\hat{\mathbf{P}}_Z|$ maximum, where $|\mathbf{P}_U|$ is small, variations in $\mathbf{P}_U$ due to noise or non-uniform sound modes (Sec. IV A) cause uncertainty in phase unwrapping, so we have plotted $\angle \hat{\mathbf{P}}_Z$ in TB9 and TB12 near the frequency of the maximum as a -0.5 -cycle step (see Sec. IV C).

- (3) $\hat{\mathbf{P}}_Z$ at nearly all locations in all bones has another magnitude maximum and -0.5 -cycle phase change near a frequency that is nearly twice the frequency of the first $|\hat{\mathbf{P}}_Z|$ maximum (15–16 kHz in TB9 and TB12, ~ 21 kHz in TB13), roughly consistent with the second resonant frequency of an open-ended tube, $\sim 2\times$ the frequency of the first resonance (e.g., Kinsler *et al.*, 1999). TB9 and TB12 show other $|\hat{\mathbf{P}}_Z|$ maxima and minima at higher frequencies.
- (4) Between the first and second resonance frequencies, $\hat{\mathbf{P}}_Z$ in all bones varies regularly with measurement location. $\angle \hat{\mathbf{P}}_Z$ decreases from near 0 at 2 mm from the umbo to -0.5 cycles or lower near the EC entrance, consistent with delay along a tube. As frequency increases, the location of minimum $|\hat{\mathbf{P}}_Z|$ moves laterally: monotonically in TB9 and approximately monotonically in TB12 and TB13. $\hat{\mathbf{P}}_Z$ in TB12 is complicated by additional $|\hat{\mathbf{P}}_Z|$

maxima and $\angle \hat{\mathbf{P}}_Z$ steps, but some of these features can be seen.

- (5) At many of the frequencies of $|\hat{\mathbf{P}}_Z|$ maxima and $\angle \hat{\mathbf{P}}_Z$ steps (Fig. 6), $|\hat{\mathbf{P}}_{TM}|$ also showed peaks with minimal values near 0 dB (Fig. 4). As noted previously, the 0 dB minima in $|\hat{\mathbf{P}}_{TM}|$ indicate a minimum in sound pressure at the umbo at these peak frequencies.

D. Effects of blocking the ear canal

In practice, measurements of EC sound pressure due to OAEs are usually performed with the EC blocked with an earplug or eartip. Transverse and longitudinal sound pressure distributions in all three ears were also determined with the EC blocked with a transparent acrylic plate as described in Sec. II C.

1. Transverse sound pressure distribution

When the EC was blocked, the range of $|\hat{\mathbf{P}}_{TM}|$ across the surface of each TM [Figs. 7(A)–7(C)] increased at many frequencies compared to the EC open case (Fig. 4), and the frequency regions with large $\hat{\mathbf{P}}_{TM}$ ranges shifted to lower frequencies. Whereas in the EC-open case the $|\hat{\mathbf{P}}_{TM}|$ range was largest (20–30 dB) between 6–10 kHz (in TB9 and TB12) or around 12 kHz (TB13), with the EC blocked the $\hat{\mathbf{P}}_{TM}$ range was relatively small in these frequency ranges and larger in lower regions: 3–6 kHz in TB9 and TB12, 4–9 kHz in TB13. The increase in $|\hat{\mathbf{P}}_{TM}|$ range (30–40 dB) in the latter frequency ranges was due to a decrease in the minimum $|\hat{\mathbf{P}}_{TM}|$ values in the EC-blocked case. The concurrence

FIG. 7. $\hat{\mathbf{P}}_{TM}$ and $\hat{\mathbf{P}}_{EC}$ ranges and phase distributions when the EC opening was blocked. (A)–(C) Maximum and minimum $\hat{\mathbf{P}}_{TM}$ (gray shading) and $\hat{\mathbf{P}}_{EC}$ (black shading) over all measurement locations in (A) TB9, (B) TB12, (C) TB13. Top panels: magnitude; bottom: phase. (D)–(F) Percentage of measurement locations at which $\angle \hat{\mathbf{P}}_{TM}$ (gray) and $\angle \hat{\mathbf{P}}_{EC}$ (black) were in-phase or out of phase with sound pressure over the umbo or on the EC axis, as defined as for Fig. 5; quadrature data not shown. Key as for Fig. 5. (D) TB9, (E) TB12, (F) TB13.

of large $\angle \hat{\mathbf{P}}_{\text{TM}}$ and large $|\hat{\mathbf{P}}_{\text{TM}}|$ ranges was similar to the EC open case.

More significantly, over much of the frequency range, the ranges of $\hat{\mathbf{P}}_{\text{EC}}$ magnitude and phase were larger with the EC blocked than with the EC open. $|\hat{\mathbf{P}}_{\text{EC}}|$ variations were larger in the blocked EC in all bones by 6–10 dB at many frequencies, especially below 9–10 kHz. Blocking the EC increased the range of transverse sound pressure variations both near the TM and in the $\mathbf{P}_{\text{EC}}$ plane 4 mm lateral to the umbo.

Distributions of $\angle \hat{\mathbf{P}}_{\text{TM}}$ and $\angle \hat{\mathbf{P}}_{\text{EC}}$ with the EC blocked [Fig. 7(D)–7(F)] showed similarities and differences with the EC-open case. The frequency ranges of low $\% \angle \hat{\mathbf{P}}_{\text{TM}}$ and $\% \angle \hat{\mathbf{P}}_{\text{EC}}$ in-phase with the EC blocked generally corresponded to frequency ranges of large $\angle \hat{\mathbf{P}}_{\text{TM}}$ and $\angle \hat{\mathbf{P}}_{\text{EC}}$ ranges in Figs. 7(A)–7(C), respectively. In TB9 and TB12 near 13–14 kHz, $\angle \hat{\mathbf{P}}_{\text{TM}}$ was out-of-phase over a majority of the TM. In frequency ranges where $\% \angle \hat{\mathbf{P}}_{\text{EC}}$ in-phase was low with the EC open, it was lower with the EC blocked, though the $\% \angle \hat{\mathbf{P}}_{\text{EC}}$ out-of-phase was generally still low.

2. Longitudinal sound pressure distribution

$\hat{\mathbf{P}}_{\text{Z}}$ measured with the EC blocked is plotted at multiple ear-canal locations vs frequency for each ear in Fig. 8. As with transverse sound pressure distributions, $\hat{\mathbf{P}}_{\text{Z}}$ magnitude and phase variations were larger in all ears (70+ dB vs 60) when the EC was blocked than when the EC was open, and $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima occurred at lower frequencies than in the open-EC case (compare to Fig. 6). $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima were larger in TB9 and TB12 than in TB13, and $|\hat{\mathbf{P}}_{\text{Z}}|$ minima were deep (>40 dB) in all ears. $\hat{\mathbf{P}}_{\text{Z}}$ in all ears has several features in common:

- (1) At frequencies below the $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum near 4–5 kHz, $\hat{\mathbf{P}}_{\text{Z}}$ is virtually constant at all locations, in contrast to the regular decrease in magnitude with distance from the

TM observed at low frequencies with the ear canal open (Fig. 6).

- (2) $\hat{\mathbf{P}}_{\text{Z}}$ in all ears at all measurement locations shows a magnitude maximum and -0.5 -cycle phase step near 4–6 kHz, about half the frequency of the first $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum with the EC open. This $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum is indicative of a sound pressure minimum (standing-wave node) at the umbo [Eq. (3)] which in this case occurs at a frequency roughly consistent with the quarter-wavelength plane-wave resonance in a closed-end tube of the same length as the EC (e.g., Kinsler *et al.*, 1999), roughly 1/2 the frequency of the open-EC half-wave resonance (Fig. 6). Again, the $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima are much greater in TB9 and TB12 (29 dB) than in TB13 (3 dB), consistent with the lower $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum in the open-EC case in TB13 (Fig. 6).
- (3) At all locations in all bones there are additional $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima and -0.5 -cycle phase step at $\sim 3\times$ and $\sim 5\times$ frequency of 1st maximum, as would be expected for resonances in a closed-end tube (e.g., Kinsler *et al.*, 1999); see Sec. IV C. In TB13 the $\angle \hat{\mathbf{P}}_{\text{Z}}$ step near 18–19 kHz is gradual and the $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum is less obvious.
- (4) Between these $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima and -0.5 -cycle $\angle \hat{\mathbf{P}}_{\text{Z}}$ steps, $\hat{\mathbf{P}}_{\text{Z}}$ at each location shows 1–2 magnitude minima and $+0.5$ -cycle phase steps at frequencies that vary regularly with distance from the TM. The frequency of the first $|\hat{\mathbf{P}}_{\text{Z}}|$ minimum increases monotonically with z , and the frequency of the second $|\hat{\mathbf{P}}_{\text{Z}}|$ minimum at each location is $\sim 3\times$ the frequency of the first minimum, also consistent with a closed-end tube (Kinsler *et al.*, 1999). These $|\hat{\mathbf{P}}_{\text{Z}}|$ minima are more obvious and deeper than in the open-EC case (Fig. 6).
- (5) As in the open-EC case, many of the frequencies of $|\hat{\mathbf{P}}_{\text{Z}}|$ maxima and $\angle \hat{\mathbf{P}}_{\text{Z}}$ steps (Fig. 8) also showed peaks in $|\hat{\mathbf{P}}_{\text{TM}}|$ with minimal values near 0 dB (Fig. 6). The downward shifting and increase in number of the frequencies where these $|\hat{\mathbf{P}}_{\text{Z}}|$ peaks occur is consistent with the

FIG. 8. (Color online) EC sound pressure $\hat{\mathbf{P}}_{\text{Z}}$ distribution as a function of frequency, measured at several longitudinal EC locations between the umbo and the blocked EC opening. (A) TB9; (B) TB12; (C) TB13; top panels: magnitude; bottom: phase. $\angle \hat{\mathbf{P}}_{\text{Z}}$ in TB9 (A) was probably contaminated by noise in $\angle \hat{\mathbf{P}}_{\text{U}}$ at the umbo due to low sound pressure at the minimum at 9 kHz there and by noise in $\angle \hat{\mathbf{P}}_{\text{Z}}$ at $|\hat{\mathbf{P}}_{\text{Z}}|$ minima; hence, $\angle \hat{\mathbf{P}}_{\text{Z}}$ is discontinuous and unwrapped to make $\angle \hat{\mathbf{P}}_{\text{Z}} \leq 0$, using $\hat{\mathbf{P}}_{\text{Z}}$ predicted by the EC model in Fig. 9 as a guide.

observation of an increase in variation in $\hat{\mathbf{P}}_{\text{TM}}$ and $\hat{\mathbf{P}}_{\text{EC}}$ when the EC is blocked.

IV. DISCUSSION

A. Description of the sound field in the ear canal with reverse stimulation

One goal of this study was to describe the EC sound field produced by OAEs. The simple descriptors we present here explain much of the EC sound field and provide a means for comparisons among ears and EC conditions with either reverse or forward stimulation.

The “reverse” sound field in the EC produced by ossicular stimulation is a combination of uniform plane waves that emanate from the TM and propagate along the ear canal (e.g., [Scheperle et al., 2008](#); [Charaziak and Shera, 2017](#)) and non-uniform sound modes that vary transversely across the TM and EC cross-section (e.g., [Rabbitt and Friedrich, 1991](#); [Fletcher, 1992](#)). Hence, $\hat{\mathbf{P}}_{\text{TM}}$ includes both plane-wave and transverse components. The non-uniform transverse modes are generated by non-uniformities in the sound source ([Keefe and Benade, 1981](#)) or in the EC cross-section along the EC length ([Farmer-Fedor and Rabbitt, 2002](#)) and propagate longitudinally in the EC with little loss if the sound frequency is above a cutoff determined by the largest transverse EC dimension. The lowest-order non-uniform mode is an antisymmetric mode in which the sound pressure on either side of a nodal diameter is of equal amplitude and opposite phase (e.g., [Keefe and Benade, 1981](#)). For a uniform tube of 3.8 mm radius (typical for human EC; [Keefe et al., 1994](#)), the cutoff frequency of this lowest order mode is 27 kHz (e.g., [Morse and Ingard, 1968](#); [Fletcher, 1992](#); [Fletcher et al., 2005](#)). Non-uniform modes excited at lower frequencies are evanescent (decay exponentially within a short distance of their generation). The exponential space constant, the distance required for an evanescent wave to decay to 37% ($1/e$) of its value, decreases as frequency decreases below the cutoff. The space constant for a 3.8-mm radius uniform tube is about 3.5 mm for a 20 kHz tone and about 2 mm at 5 kHz ([Morse and Ingard, 1968](#); [Fletcher, 1992](#)). In our experiments, the TM was driven by the ossicles, so it is very likely that manubrium motion generated substantial transverse variations in TM motion that vary with frequency, even at frequencies as low as a few hundred Hz ([Cheng et al., 2012](#); [Cheng et al., 2019](#)). These transverse variations in TM motion very likely generated non-uniform sound waves.

1. Near the TM

A prominent feature of the reverse-driven sound field near the TM is the presence of large spatial variations in sound pressure across the surface of the TM in narrow frequency bands at relatively low frequencies. The $\hat{\mathbf{P}}_{\text{TM}}$ maps in Fig. 2 and the mean $\hat{\mathbf{P}}_{\text{TM}}$ distributions in Fig. 3 show significant spatial variations in some frequency ranges, and the anterior-posterior mean $\angle \hat{\mathbf{P}}_{\text{TM}}$ distribution is consistent with a contribution from the first antisymmetric non-uniform mode. With an open EC, the range of $|\hat{\mathbf{P}}_{\text{TM}}|$ is greater than

20 dB at multiple frequencies between 6 and 15 kHz (Fig. 4). At some frequencies (e.g., 9 kHz in TB9, 7.5 and 9.5 kHz in TB12) the maximum $|\hat{\mathbf{P}}_{\text{TM}}|$ is greater than 15 dB and the minimum $|\hat{\mathbf{P}}_{\text{TM}}|$ is near 0 dB, which implies that the sound pressure near the TM is nearly a minimum at the umbo. Such frequencies generally correspond to a $|\hat{\mathbf{P}}_{\text{Z}}|$ maximum and -0.5 -cycle $\angle \hat{\mathbf{P}}_{\text{Z}}$ step at many or all lateral locations (Fig. 6).

The size of the spatial variations in $|\hat{\mathbf{P}}_{\text{TM}}|$ at various frequencies reveals the relative contribution of planar and non-uniform sound modes at those frequencies. At many frequencies, $|\hat{\mathbf{P}}_{\text{TM}}|$ over the TM surface is nearly uniform (a range of less than 5 dB), which indicates that the sound field near the TM is dominated by uniform plane waves. At other frequencies, the $|\hat{\mathbf{P}}_{\text{TM}}|$ range is on the order of 6–10 dB (a factor of 2 to 3), which implies a contribution of non-uniform modes to the total sound field at the TM comparable to the contribution of plane waves. In the 6–10 kHz range, however, the sound pressure near the umbo is a minimum (standing-wave node; Fig. 6), and the contribution of transverse modes to the total sound field at the TM should dominate. The low percentage of $\mathbf{P}_{\text{TM}}$ in phase with the umbo ($\% \angle \hat{\mathbf{P}}_{\text{TM}} \approx 0$) in these ranges (Fig. 5) is consistent with the sound pressure near the TM dominated by non-uniform modes. Similar relationships exist when the ear canal is blocked: At frequencies of maxima in the longitudinal dependence of the sound pressure $|\hat{\mathbf{P}}_{\text{Z}}|$ (due to minima in $|\mathbf{P}_{\text{U}}|$ at those frequencies), the variations in $\hat{\mathbf{P}}_{\text{TM}}$ are large, consistent with a significant influence of transverse variations on $\hat{\mathbf{P}}_{\text{TM}}$.

2. 1–4 mm distal to the TM

As discussed above, non-uniform modes generated at the TM that contribute significantly to $\hat{\mathbf{P}}_{\text{TM}}$ variations will decay and contribute significantly less to $\hat{\mathbf{P}}_{\text{EC}}$ variations. Our observation that $|\hat{\mathbf{P}}_{\text{EC}}|$ variations in the transverse EC plane in the open EC are considerably lower than $\hat{\mathbf{P}}_{\text{TM}}$ variations at nearly all frequencies below 16 kHz (Fig. 4) is consistent with the decay of non-uniform modes at locations distal to the TM. The observation of larger $\hat{\mathbf{P}}_{\text{EC}}$ variations at higher frequencies than at low is consistent with less dissipation of non-uniform modes between the TM and the EC transverse plane (longer space constant) at frequencies closer to the EC cutoff frequency.

3. Longitudinally along the EC axis

The frequency and spatial dependence of $\hat{\mathbf{P}}_{\text{Z}}$ and its sensitivity to blocking the ear canal appear to have much in common with longitudinal sound pressure variations along a uniform tube of length comparable to the EC. This similarity and any differences will be investigated in Sec. IV C, where we quantitatively compare these data with predictions of a tube model.

4. Effect of blocking the EC termination

Blocking the EC affected not only the spatial dependence of $\hat{\mathbf{P}}_{\text{Z}}$ but also spatial variations in $\hat{\mathbf{P}}_{\text{TM}}$ and $\hat{\mathbf{P}}_{\text{EC}}$. When the

ear canal was blocked, both the $\hat{P}_{TM}$ and $\hat{P}_{EC}$ ranges increased substantially in some frequency ranges, especially below 8 kHz, in all ears relative to the open-EC case, and the $\% \angle \hat{P}_{TM}$ and $\% \angle \hat{P}_{EC}$ in-phase decreased substantially in wide frequency ranges. As discussed later, a significant fraction of the EC termination-induced changes in the frequency dependence of $\hat{P}_{TM}$ and $\hat{P}_{EC}$ are correlated with EC termination-induced shifts in the frequencies of $|\hat{P}_Z|$ maxima: In either termination condition, the frequencies of the peaks in $|\hat{P}_Z|$ are similar to the frequencies of the peaks in $|\hat{P}_{TM}|$ and $|\hat{P}_{EC}|$. Importantly, the peaks in $|\hat{P}_Z|$ are due to a minimum in the sound pressure measured near the umbo. These termination-induced changes in the spatial variability of sound pressure have important implications for measurement of otoacoustic emissions, discussed further in Sec. IV E below.

B. Comparison to sound fields with forward (sound) stimulation

1. Transversely across the TM and ear canal

The nature of transverse $\hat{P}_{TM}$ and $\hat{P}_{EC}$ variations with frequency is much different between reverse and forward stimulation. Measurements in bones TB12 and TB13 with sound stimulation showed that spatial variations in $\hat{P}_{TM}$ and $\hat{P}_{EC}$ are consistent with a longitudinal standing-wave node (from interactions with the oblique TM terminating the EC) that moves medially across measurement locations near the TM as frequency increases (Ravicz *et al.*, 2014, Fig. 5): $\hat{P}_{TM}$ and $\hat{P}_{EC}$ were virtually constant across the TM at frequencies below 7–10 kHz and showed a deep magnitude minimum and +0.5-cycle phase range increase near 15 kHz. Such behavior is in contrast to the much more irregular frequency-dependent variations in $\hat{P}_{TM}$ and $\hat{P}_{EC}$ range that result from the nonuniform TM motion with reverse stimulation (Fig. 4). One interesting consequence is that $\hat{P}_{TM}$ variations between about 13 and 16 kHz and above 20 kHz are smaller with reverse stimulation than with forward.

2. Longitudinally along the ear canal

Measurements of the longitudinal sound pressure distribution in bones TB12 and TB13 with forward stimulation (“longitudinal P_{EC} ” in Ravicz *et al.*, 2014) showed a standing-wave pattern similar to that predicted for a simple closed-ended cylindrical tube: the sound pressure was fairly uniform at low frequencies, and a node appeared near the EC entrance at 6–7 kHz (where the EC length corresponds to approximately 1/4 wavelength) and moved medially at higher frequencies. $\hat{P}_Z$ with reverse stimulation and an open ear canal (Fig. 6) shows a longitudinal distribution similar to a standing-wave pattern predicted for an open-ended tube of the same length, as described below.

C. Comparison of longitudinal $\hat{P}_Z$ variations to tube models of the EC

To extend the results of our measurements to real ears, we compare our results to a mathematical transmission-line model of the ear canal as seen from the umbo, described in

the Appendix, that takes radiation impedance, viscous losses, and thermal losses into account.

1. Model predictions of longitudinal P_Z variations in experimental preparation

a. Ear canal open. The $\hat{P}_Z$ predicted by the model [referred to sound pressure at the TM $P(l)$] for an open EC is shown in Fig. 9(A) for a 17-mm long EC (as in ears TB9 and TB12). A comparison with Fig. 6 shows that the simple EC model predicts most of the pertinent features of the measurements in all three ears: (1) At low frequencies, monotonic $|\hat{P}_Z|$ decrease with distance from the EC opening and $\angle \hat{P}_Z$ near 0; (2) $|\hat{P}_Z|$ maximum and -0.5 -cycle $\angle \hat{P}_Z$ step (resonance) near 9 kHz; (3) another $|\hat{P}_Z|$ maximum and -0.5 -cycle $\angle \hat{P}_Z$ step at approximately twice the frequency of the first resonance; and (4) location-dependent $|\hat{P}_Z|$ minima above the first resonant frequency. These features occur at higher frequencies in a model of the shorter ear canal in TB13 (not shown), consistent with measurements (Fig. 6), and at lower frequencies in a model EC of 25-mm length (typical in human subjects and patients per Keefe *et al.*, 1994; Faddis, 2008; Rasetschwane and Neely, 2011) to mimic the intact human EC.

b. Ear canal blocked. The $\hat{P}_Z$ predicted by the model for a blocked EC is shown in Fig. 9(B) for the 17-mm long EC. A comparison with Fig. 8 shows that this same model provides a fairly good prediction of the uniformity of low-frequency $\hat{P}_Z$, the frequencies of $|\hat{P}_Z|$ maxima and minima and $\angle \hat{P}_Z$ transitions, and the higher frequencies of these features in the shorter ear canal, though the match is not as good as for the open EC.

The tube model predicts the larger $|\hat{P}_Z|$ extrema and sharper $\angle \hat{P}_Z$ transitions in the blocked EC vs the open EC. This is reasonable because the higher Z_{term} in the blocked EC causes the absolute EC sound pressure to be higher, while the lower radiation impedance terminating the open tube allows significant losses, especially at higher frequencies. These results suggest that the longitudinal $\hat{P}_Z$ distribution is determined primarily by the acoustics of the ear canal. This simple model provides a useful description of the EC longitudinal sound field and provides a basis for predictions in real ear canals.

c. Effect of open middle ear. It has been shown that the state of the middle ear cavity (open, closed, reduced) affects the middle-ear input impedance Z_{ME} and the sound pressure transformation from EC to near the TM for forward sound stimulation (e.g., Voss *et al.*, 2000; Keefe *et al.*, 1994; Stepp and Voss, 2005; Lewis and Neely, 2015; Feeney *et al.*, 2017). In the reverse-stimulation case, where a displacement source moves the ossicles and the TM, the EC sound pressure distribution is independent of Z_{ME} (see model description in the Appendix).

2. Model predictions of longitudinal P_Z variations in real ears with different ear canal terminations

The close fit between model predictions and measurements in shortened but otherwise natural ear canals supports

FIG. 9. (Color online) (A) and (B) $\hat{P}_Z$ distribution predicted for an EC of 17-mm length (as in TB9 and TB12; see Fig. 6) by the lossy transmission-line model with the entrance (A) open or (B) blocked. (C) EC of 25-mm length terminated by the characteristic impedance of the model EC tube. (D) $\hat{P}_Z$ distribution predicted for an EC with an ER10-14 foam earplug inserted to a depth 18.3 mm from the TM (as in Schepferle *et al.*, 2011); line code as for (A). Top panels: magnitude; bottom: phase.

the use of the model for predictions of the longitudinal $\hat{P}_Z$ distribution in real ears with various terminations. Figure 9 also shows $\hat{P}_Z$ predictions in an EC model of 25-mm length with a “matched” nonreflective termination Z_0 equal to the characteristic⁷ impedance of the model tube [Fig. 9(C)] and shortened and terminated with the impedance of a foam earplug [(Etymotic) ER10-14; Schepferle *et al.*, 2011]⁸ to mimic clinical measurement conditions [Fig. 9(D)]. As a check, the impedance looking out the open EC from the TM Z_{EC} predicted by this model is qualitatively similar to previous models, see the Appendix.

The standing-wave patterns in Figs. 9(A) and 9(B) result from reflections from the EC termination because Z_{term} is not equal to the EC characteristic impedance Z_0 . The matched-impedance condition, in which we set the model $Z_{term} = Z_0$, produces a constant $|\hat{P}_Z|$ and smoothly accumulating $\angle \hat{P}_Z$ with frequency at all EC locations [Fig. 9(C)] as expected.

The case when the EC is occluded by an audiometric earplug [Fig. 9(D)] is modeled by setting Z_{term} to the impedance of an ER10-14 foam earplug (Schepferle *et al.*, 2011), which is between the high impedance of a rigid termination and Z_0 . Z_{term} is lower than with the rigid termination [Fig. 9(B)], the $|\hat{P}_Z|$ extrema are shallower (~ 15 dB), and $\angle \hat{P}_Z$ transitions are smoother than in either the open or rigidly terminated cases.⁹ The predictions in Figs. 9(C) and 9(D)

indicate that longitudinal EC sound pressure variations can be reduced by minimizing reflections from the EC termination, i.e., by making the terminating impedance close to the characteristic impedance of an EC tube.

D. Transverse sound pressure variations revealed by plane-wave minima

As discussed in Sec. IV C above, the maximum in $|\hat{P}_Z|$ at a natural frequency of the EC is due to a minimum in the sound pressure near the umbo P_U [see Eq. (3)]—a node in the longitudinal standing-wave pattern in the EC occurs near the umbo. In this section we show that, because the sound pressure at any point in the ear canal is the sum of the plane-wave (longitudinal) and nonuniform (transverse) sound pressures, the transverse variations are most obvious at frequencies and locations where the longitudinal sound pressures are small.

1. At the TM

A comparison of the earlier figures suggests that, for each bone and EC termination (open or blocked), magnitude maxima in the normalized sound pressure along the TM surface occur approximately at frequencies where the longitudinal EC sound pressure distribution shows a magnitude minimum at the umbo. For instance, the frequencies of

$|\hat{P}_{TM}|$ maxima in Fig. 4 (EC open) are similar to the frequencies of $|\mathbf{P}_U|$ minima in Fig. 6, and the frequencies of $|\hat{P}_{TM}|$ maxima in Fig. 7 are similar to those of $|\mathbf{P}_U|$ minima in Fig. 8 (EC blocked). This similarity suggests that the transverse sound pressure variations near the TM are best revealed at frequencies where the longitudinal sound pressure is small.

To explore this relationship, the frequencies of $|\hat{P}_{TM}|$ maxima are plotted against the frequencies of $|\mathbf{P}_U|$ minima in both EC conditions for each bone in Fig. 10. From Sec. IV C, the $|\mathbf{P}_U|$ minimum and $+1/2$ -cycle $\angle \mathbf{P}_U$ step at a natural frequency of the EC produces a maximum in $|\hat{P}_Z|$ where $|\hat{P}_Z| > 0$ dB at all or nearly all EC locations and $\angle \hat{P}_Z$ has a $-1/2$ -cycle step. We consider frequencies of $|\hat{P}_{TM}|$ maxima that meet two or more of the following three criteria: (i) the maximum $|\hat{P}_{TM}|$ has a well-defined peak; (ii) the minimum $|\hat{P}_{TM}|$ is near 0 dB (i.e., $|\mathbf{P}_{TM}|$ is smallest near the umbo, see Fig. 4), and (iii) $\angle \hat{P}_{TM}$ range is at least 0.5 cycle.¹⁰

Figure 10 demonstrates that nearly all $|\hat{P}_{TM}|$ maxima occur at frequencies that are similar to those of the $|\mathbf{P}_U|$ minima: nearly all of the points plot on or near the diagonal line that indicates equal $|\hat{P}_{TM}|$ maximum and $|\mathbf{P}_U|$ minimum frequencies. This relationship is strongly true for the open EC and generally true for the blocked EC and supports the idea that $|\hat{P}_{TM}|$ maxima are related to $|\mathbf{P}_U|$ minima.

Figure 10 also shows that the relationship between $|\mathbf{P}_U|$ minimum frequencies with the EC open or blocked is consistent with the relationship among open- or closed-end tube resonant frequencies. In each bone, the maxima in the open EC occur roughly at frequencies that differ by a factor of 2. With the EC blocked, the lowest maxima frequency is roughly half the lowest maxima frequency with the EC open, and additional blocked-EC maxima frequencies are approximately $3\times$ and $5\times$ the lowest frequency.

In TB9 and TB12, there were one or more $|\hat{P}_{TM}|$ maxima that had no $|\mathbf{P}_U|$ minima associated with them [that are plotted near vertical axis in Figs. 10(A) and 10(B)], and TB13 had a $|\mathbf{P}_U|$ minimum with no associated $|\hat{P}_{TM}|$ maximum [plotted near horizontal axis in Fig. 10(C)]. These unassociated maxima were more common in the blocked EC than in the open EC. This greater variability in results with the EC blocked is consistent with the larger ranges of $\hat{P}_{TM}$

and $\hat{P}_Z$ variations in the blocked EC (Figs. 7 and 8) versus the open EC.

The analysis of Fig. 10 supports the ideas that (1) the EC sound field is a combination of plane waves and nonuniform modes (Sec. IV A) and (2) low plane-wave sound pressure near the TM at the EC natural frequencies allows sound pressure from nonuniform modes to dominate the sound field near the TM at those frequencies, which results in large observable variations in $\hat{P}_{TM}$. This suggests that the contribution of nonuniform modes to the total sound pressure would be less important if the uniform plane-wave pressure at the TM were larger. Previous work and Sec. IV C point out that reducing sound pressure reflection at the EC termination increases $|\mathbf{P}_U|$ at the natural frequencies [Figs. 9(C) and 9(D)] and reduces the spatial and frequency variation in the magnitude of the longitudinal wave throughout the ear canal. Such increases in minimum $|\mathbf{P}_Z|$ should reduce the range of transverse sound pressure variations near the TM and in other locations in the ear canal.

2. More laterally in the ear canal

The range of $\hat{P}_{EC}$ in a transverse EC plane ~ 4 mm from the TM in the open EC (Fig. 4) is generally much smaller than the range of $\hat{P}_{TM}$ but still shows magnitude maxima in some fairly narrow frequency ranges. The frequency ranges of $|\hat{P}_{EC}|$ maxima generally correspond to frequencies of minima in $|\hat{P}_Z|$ measured ~ 4 mm from the TM (Fig. 6), most strikingly in TB9 at 11 and 20 kHz and in TB12 at 8 and 17 kHz. The influence of non-uniform modes at these more distal EC locations can also be reduced by a better-matched EC termination that reduces reflections and increases $|\mathbf{P}_{EC}|$ at the standing-wave nodes (reduces the depth of $|\hat{P}_Z|$ minima along the EC) at all locations.

3. Predictions in real ears

The relationship described above between large $\hat{P}_{TM}$ variability and $\mathbf{P}_U$ minima should exist in real ear canals also. From the model predictions in Fig. 9, we would expect a downward shift in the frequencies of large $\hat{P}_{TM}$ range corresponding to the downward shift of resonance frequencies

FIG. 10. Comparison of frequencies of $|\hat{P}_{TM}|$ maxima to frequencies of $|\mathbf{P}_U|$ minima ($|\hat{P}_Z|$ maxima), with the EC open (open symbols) or blocked (closed symbols), in (A) TB9, (B) TB12, and (C) TB13. The dot-dashed diagonal line represents a perfect correspondence between frequencies of $|\hat{P}_{TM}|$ peaks and $|\mathbf{P}_U|$ minima. Symbols plotted near the vertical axis in (A) and (B) denote frequencies of $|\hat{P}_{TM}|$ peaks where no $|\mathbf{P}_U|$ minimum was observed; the symbol near the horizontal axis in (C) denotes a $|\mathbf{P}_U|$ minimum in TB13 at a frequency where no $|\hat{P}_{TM}|$ peak was observed.

in the longer EC, to 6–7 kHz in the open EC and 4–5 kHz with the EC blocked.

E. Implications for measuring OAEs

Though OAEs have been shown to be useful clinically for screening for cochlear dysfunction, large test-retest differences have limited their applicability (e.g., Konrad-Martin *et al.*, 2016; Charaziak and Shera, 2017). Much of the test-retest difference seems to be due to variations in ear-canal sound pressure among different longitudinal measurement locations, and between measurement locations and the TM (e.g., Siegel, 1994), for both the OAEs and the stimuli that elicit them (Charaziak and Shera, 2017). The usual approach to minimize longitudinal variations within the frequency range of clinical interest is to try to position a microphone as close to the TM as possible, but in practice the closest approach is still several mm away (e.g., Souza *et al.*, 2014).

Several authors have developed schemes to detect or predict and correct for longitudinal variations, including inferring the EC cross-section area function from reflectance measurements and developing a mathematical model of individual ECs (Rasetshwane *et al.*, 2015; Scheperle *et al.*, 2011). Simple tube or more complicated models have been used to extract the forward (stimulus) pressure wave from the sound field (Souza *et al.*, 2014), and similar techniques have been used to extract the backward-traveling OAE wave from the EC sound pressure (Charaziak and Shera, 2017). Though some of these techniques have been successful in correcting for longitudinal $\hat{P}_Z$ variations in the EC, they do not address transverse $\hat{P}_{TM}$ variations.

We have shown here for reverse stimulation (which mimics OAEs), large transverse spatial variations occur in EC sound pressure close to the TM but generally dissipate by 4 mm from the TM. Furthermore, we show that both $\hat{P}_{TM}$ and $\hat{P}_Z$ variations are larger and can occur at lower frequencies if the EC is blocked (Sec. III D). These results demonstrate that, though locating the tip of an emission probe tube closer to the TM may reduce uncertainty due to longitudinal $\hat{P}_Z$ variations, transverse variations emanating from the TM are more problematic there. Locating the tip of the emission probe at least 4 mm from the TM should reduce the effect of such transverse variation but require that the effect of probe insertion depth be accounted for, for example, by estimating the emitted sound pressure (Charaziak and Shera, 2017).

The decrease in the frequencies of significant transverse and longitudinal sound pressure variations when the EC is blocked suggests that sound reflections from an OAE probe that blocks the ear canal increases uncertainty in measurements of both OAEs and elicitor levels (see also Dreisbach and Siegel, 2001; Scheperle *et al.*, 2011). Charaziak and Shera (2017) codified this by computing the transformation from the emitted OAE sound pressure OAE_{EPL} to that measured more distally in the EC OAE_{SPL} as

$$OAE_{EPL} \cong OAE_{SPL} \frac{(1 - RR_S)}{T(1 + R_S)}, \quad (4)$$

where R and R_S are the pressure reflectances of the middle ear and the OAE probe respectively, and T is a delay term

[Charaziak and Shera, 2017, Eq. (2)]. Reducing sound reflection from the OAE probe (reducing R_S) reduces the difference between OAE_{SPL} and OAE_{EPL} . In the limiting case where $R_S = 0$ [no reflection, as in Fig. 9(C)], $|OAE_{SPL}| = |OAE_{EPL}|$. In this way, uncertainties in both OAEs and their elicitors could be reduced by minimizing reflections from the OAE probe.

Of course, transverse nonuniformities in sound pressure can also come from longitudinal variations in the EC cross-section area (Rabbitt and Friedrich, 1991; Farmer-Fedor and Rabbitt, 2002). These nonuniformities generated within the ear canal will also propagate small finite distances, but the locations where they are maximal will depend strongly on individual anatomy (e.g., Rasetshwane *et al.*, 2015), and it will be harder to define a location where OAEs will be less affected by ear-canal related non-uniformities in transverse sound pressure.

V. SUMMARY AND CONCLUSIONS

- (1) With reverse mechanical stimulation of the ossicles, the spatial sound pressure distribution within the ear canal varies substantially, in narrow frequency bands, even at frequencies as low as 2–3 kHz.
- (2) Reverse mechanical stimulation of the TM results in large spatial variations in sound pressure magnitude and phase transversely across the TM (Figs. 2–5). These $\hat{P}_{TM}$ variations are due to non-uniform sound modes generated by complex motion of the TM (Cheng *et al.*, 2012; Cheng *et al.*, 2019). These variations are different in nature and occur at lower frequencies than those seen with forward sound stimulation (Fig. 9).
- (3) Transverse variations in the normalized sound pressure within the ear canal $\hat{P}_{EC}$ in a transverse EC plane ~ 4 mm from the umbo are smaller than those observed near the TM, consistent with the decay of evanescent non-uniform sound modes generated near the TM (Figs. 4 and 5).
- (4) Large variations in normalized longitudinal sound pressure $\hat{P}_Z$ magnitude and phase were observed (Fig. 6), consistent with a simple model of standing waves in the EC (Fig. 9). These variations include $|\hat{P}_Z|$ maxima (produced by sound pressure minima near the umbo) at the natural frequencies of the ear canal.
- (5) The frequencies of the highest $\hat{P}_{TM}$ variations generally correspond to plane-wave natural frequencies, at which the sound pressure near the TM is a minimum ($|\hat{P}_Z|$ is a maximum) (Figs. 4, 6, and 10).
- (6) Blocking the EC increases the complexity of the sound field: Transverse variations near the TM and more distally in the EC were larger at lower frequencies than with the EC open (Fig. 7). Longitudinal variations consistent with standing waves were also larger (Fig. 8), and the frequencies of extrema shifted to lower values in a manner consistent with the predicted change in the natural frequencies of a tube when the end is blocked (Fig. 9). Associated with this shift in $\hat{P}_Z$ natural frequencies is a shift in the frequencies of the largest transverse $\hat{P}_{TM}$ variations (Fig. 10).

- (7) The choice of the location to measure OAE primary stimuli and response levels involves a tradeoff between transverse and longitudinal EC sound pressure variations. Reducing reflections from the OAE probe will increase EC sound pressure at longitudinal minima (Fig. 9), which may reduce the relative contribution of transverse sound pressure variations to the total sound field and allow more accurate measurement of OAEs.

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APPENDIX

To extend the results of our measurements of longitudinal EC sound pressure variations to real ears, we use a mathematical model of the ear canal and middle ear as seen from the TM, shown in Fig. 11(A). The stimulator drives the ossicles and TM to generate a volume velocity U_U at the TM. The model assumes a plane wave sound field, so sound pressure P_U in the EC near the umbo is the same over the entire TM. P_U is related to U_U by the impedance Z_{EC} looking out through the ear canal.

The EC is modeled as a cylindrical tube of length l and constant cross-section area for simplicity, using an acoustic two-port transmission-line matrix model (e.g., Egolf, 1977). In such a model, a transmission matrix T describes the transformation of P_U and U_U from near the umbo (a distance l from the EC termination) to the sound pressure P_{term} and volume velocity U_{term} at the EC termination at $z = 0$,

$$\begin{Bmatrix} P_U \\ U_U \end{Bmatrix} = T(l) \begin{Bmatrix} P_{term} \\ U_{term} \end{Bmatrix} = \begin{bmatrix} A(l) & B(l) \\ C(l) & D(l) \end{bmatrix} \begin{Bmatrix} P_{term} \\ U_{term} \end{Bmatrix}. \quad (A1)$$

The elements of T (commonly denoted by A , B , C , and D) are functions of frequency, the radius a of the tube, and the relevant EC length. The sound pressure transformation between P_U and P_{term} is computed by expanding the top part of Eq. (A1),

$$P_U = A(l)P_{term} + B(l)U_{term} \quad (A2a)$$

or, dividing by P_{term} and using $Z_{term} = P_{term}/U_{term}$,

$$P_U/P_{term} = A(l) + B(l)/Z_{term}. \quad (A2b)$$

Similarly, $P(z)$ at any location z within the EC [see Fig. 11(B)] is computed from Z_{term} similar to Eq. (A2b) by substituting z for l ,

$$P(z)/P_{term} = A(z) + B(z)/Z_{term}, \quad (A2c)$$

FIG. 11. Acoustic circuit- and two-port EC model used to predict P_Z distribution. (A) Volume velocity U_U at the TM resulting from driving the ossicles creates sound pressure P_U near the umbo that depends on the lateral load (EC impedance) Z_{EC} . P_U is the sound pressure at the EC termination P_{term} transformed by the EC acoustic two-port transmission matrix T using the terminating impedance Z_{term} . Note that P_U is independent of the medial load (ME input impedance) Z_{ME} . (B) The sound pressure $P(z)$ at EC location z is computed from the transformation of P_{term} by $T(z)$ at location z as described in the text.

and the sound pressure transformation $\hat{P}_Z(z)$ between $P(z)$ at z and P_U near the TM is computed by dividing Eq. (A2c) by Eq. (A2b):

$$\hat{P}_Z(z) = [P(z)/P_{term}]/[P_U/P_{term}]. \quad (A3)$$

The EC model uses a tube radius a of 3.8 mm (cross-section area of 45 mm^2), typical of recent measurements of the EC midsection by different methods (Stinson and Lawton, 1989; Keefe *et al.*, 1994; Rasetshwane and Neely, 2011), and length $l = 13\text{--}17$ mm to match the measured ECs or 25 mm to match the typical unmodified human ear. Z_{term} for the open EC is the radiation impedance from a “long tube” [Beranek, 1986, Eqs. (5.20)–(5.33)]; for the blocked EC, Z_{term} is very large. Z_{EC} and the sound pressure gain from free field to eardrum predicted for a 25-mm-long EC by this simple model are not much different from predictions of more complicated models: The frequencies of the $|Z_{EC}|$ minima are slightly lower than those predicted by the Siebert (1973) two-tube model, and our model does not predict the smaller high-frequency minima of the Shaw (1974) and Keefe *et al.* (1994) models that include a larger-diameter tube to represent the concha, but our simple model captures the main features ($|Z_{EC}|$ amplitude, frequencies of first few $|Z_{EC}|$ maxima and minima) of these more complicated models.

¹The consequences of this repair were minimal in this experiment in which the ossicles were driven mechanically.

²Sound pressures P are complex variables with real and imaginary parts (expressible as magnitude $|P|$ and phase $\angle P$) and are shown in bold type.

³See supplementary material at <https://doi.org/10.1121/1.5094776> for TB9 (SuppPubmm1.mov), TB12 (SuppPubmm2.mov), and TB13 (SuppPubmm3.mov).

⁴The complex mean was computed by separately averaging the real and imaginary parts of $\hat{P}_{TM}$ at each location; the magnitude and phase of this mean were then extracted and plotted.

⁵“Quadrature” is defined as $\angle \hat{P}$ between $+0.125$ and $+0.375$ cycle or between -0.125 and -0.375 cycle.

⁶Note that $\hat{P}_Z$ was previously denoted “longitudinal P_{EC} ” in Ravic *et al.* (2014). We find it more instructive to present the data as frequency responses rather than constructing a map of longitudinal $\hat{P}_Z$ variations per the previous paper.

⁷Called “surge impedance” in Neely’s papers.

⁸The source impedance of the ER10-14 presented by [Scheperle et al. \(2011\)](#) does not include the effect of evanescent modes (e.g., [Nørgaard et al., 2018](#)). For our purposes, this omission is not important.

⁹The source impedance of the ER10D audiometric earbud is only slightly higher than that of the ER10-14 ([Scheperle et al., 2011](#)), so the standing-wave pattern should be only slightly peakier.

¹⁰The $|\hat{P}_{TM}|$ peaks in TB13 with the EC open do not quite meet these criteria, but they represent the closest examples.

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