Spontaneous otoacoustic emissions are generated by active oscillators clustered in frequency plateaus

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SOAEs simulated with an active and nonlinear transmission line model of the human cochlea stem from self-sustained oscillators grouped in frequency plateaus. The analogy of a model of lizard SOAE generation and human SOAE generation allow to test current theories of SOAE generation.

**MODELS**

**Linear array of oscillators (LAM)**

The formation of frequency plateaus was investigated using a LAM written in the normal form of a Hopf bifurcation (Vilfan & Duke, 2008; all parameters taken from Wil & van Dijk, 2012):

\[ \dot{x}_j = (k_x + \sum_{\ell=1}^{N} \kappa_x (\dot{x}_\ell - x_j - \Delta x_j)) \frac{\dot{x}_j}{|\dot{x}_j|} + g(x_j) - f_j(t) \]

\[ f_j(t) = \sum_{l=1}^{N} \frac{\kappa_f}{|x_l|^{\frac{m_f}{2}}} \left( \frac{|\dot{x}_j|}{|x_l|^{\frac{m_f}{2}}} \right)^{m_f} \]

\[ g(x_j) = \begin{cases} 0 & \text{for } |x_j| < x_{th} \\ \frac{\kappa_g}{|x_j|^{\frac{m_g}{2}}} |x_j|^{m_g} & \text{for } |x_j| \geq x_{th} \end{cases} \]

\[ \Delta x_j = \frac{\kappa_{\Delta x}}{\kappa_x} (x_{th} - |x_j|) \]

\[ \kappa_x > 0, \kappa_f > 0, \kappa_g > 0, \kappa_{\Delta x} > 0, x_{th} > 0, m_f > 0, \]

\[ m_g > 0, x_j \in \mathbb{R}, t \in \mathbb{R} \]

The model equations were solved in the time domain using the fourth Euler method with a step width of \( \Delta t = 2\pi/(360 \cdot \omega) \) with \( \omega = (\omega_0 + \omega_1)/2 \).

**Transmission line model (TM)**

A nonlinear and active TM with 1000 segments and included roughness of the cochlea was used to simulate SOAEs (all parameters taken from Epp et al., 2010):

\[ \dot{x}_j = m_j \dot{x}_j + d_j(x_j) x_j + g_j(x_j)(t - \ldots) \]

\[ f_j(t) = \sum_{l=1}^{N} \frac{\kappa_f}{|x_l|^{\frac{m_f}{2}}} \left( \frac{|\dot{x}_j|}{|x_l|^{\frac{m_f}{2}}} \right)^{m_f} \]

\[ g_j(x_j) = \begin{cases} 0 & \text{for } |x_j| < x_{th} \\ \frac{\kappa_g}{|x_j|^{\frac{m_g}{2}}} |x_j|^{m_g} & \text{for } |x_j| \geq x_{th} \end{cases} \]

\[ \Delta x_j = \frac{\kappa_{\Delta x}}{\kappa_x} (x_{th} - |x_j|) \]

\[ \kappa_x > 0, \kappa_f > 0, \kappa_g > 0, \kappa_{\Delta x} > 0, x_{th} > 0, m_f > 0, \]

\[ m_g > 0, x_j \in \mathbb{R}, t \in \mathbb{R} \]

The model equations were solved in the time domain with a rate of 400 kHz using a modified 4-th order Runge-Kutta method.

**METHODS**

- Formation of frequency plateaus using the LAM model (see Wil & van Dijk, 2012).
- Simulation of SOAEs using the TM with introduced roughness (see Epp et al., 2010).
- Analysis of oscillations of all elements of the TM in the frequency domain.
- Extraction of frequency with maximum amplitude for each TM segment.

**REFERENCES**


**CONCLUSION**

Comparison of LAM with TM approaches are helpful to investigate the generation and theories of SOAEs. Similarity between model of Lizard and human SOAE generation suggests common mechanisms underlying SOAE generation. Multiple oscillators clustered in frequency plateaus are potential sources of SOAEs measured outside the inner ear. The LAM and TM suggest that SOAEs are mainly due to traveling waves into the cochlear without standing waves.

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**DISCUSSION**

- Self-sustained oscillations in LAM and TM
- Nonlinear feedback stiffness term
- Self-sustained oscillations with properties similar to SOAEs of humans found in a linear array of coupled oscillators.
- Nonlinear effective damping
- Tonsotopically arranged self-sustained oscillations observed in TM as SOAEs and as self-sustained oscillations of the segments.
- Frequencies of SOAEs match exactly with frequencies of the self-sustained oscillators.
- Generation of frequency plateaus indicates similar nonlinear interactions between oscillators in LAM and the TM.

- Frequency clustering in LAM and TM
- Frequency clusters of TM tonotopically arranged with frequency separation similar to spectral spacing of SOAEs in humans.
- Supports hypothesis of common underlying mechanisms of SOAE generation in Lizards and humans.
- Frequency clusters in TM tonotopically arranged with multiple plateaus at same frequency across segments.

**RESULTS**

**RESULT: SELF-SUSTAINED OSCILLATIONS AND SOAE**

**RESULT: FREQUENCY CLUSTERING**

**RESULT: TRAVELING VS STANDING WAVES**

**FIGURE:** Spectra of the simulated ear canal pressure corresponding to the self-sustained oscillations of the cochlear partitions. Frequencies in the ear canal waxlly match the frequencies of the self-sustained oscillators. The most shows the characteristic spectral width of SOAEs.

**FIGURE:** Spectrums of the simulated ear canal pressure corresponding to the self-sustained oscillations of the cochlear partitions. Frequencies in the ear canal match the frequencies of the self-sustained oscillators. The most shows the characteristic spectral width of SOAEs.

**FIGURE:** Oscillations of the cochlear partitions without external oscillation. The maximum frequencies reflect the tonotopic organization of the simulated cochlear and the vertical strip shows the energy of oscillations at specific places travelling from base to apex.