

# **A computational model of the responses of octopus neurons in the PVCN**

**Nima Salimi<sup>1\*</sup>, Muhammad S. A. Zilany<sup>1</sup>**

<sup>1</sup> Department of Biomedical Engineering, University of Malaya, Kuala Lumpur, Malaysia

\* Corresponding author.

Email: nimasalimi64@gmail.com

## **Abstract**

Acoustic information can be detected and processed through the auditory pathway in a very fast and complicated way. A large number of studies have investigated sound encoding at different levels of the auditory system by recording direct neural responses to different types of stimuli. However, processing of more complex stimuli at higher auditory centres is not well understood yet. Computational modeling has emerged as a new approach in order to obtain at least some insight into mechanisms underlying processing of complex sounds such as speech, animal vocalization, and music. In this study, the main goal is to develop a phenomenological and computer-based model of octopus neurons in the posterior ventral cochlear nucleus to simulate the physiological responses to simple and complex stimuli. Octopus cells receive synaptic inputs from a number of auditory nerve (AN) fibers; as a result, an AN model developed by Zilany and colleagues has been used to provide input to the proposed model. The summation of weighted outputs from the AN model has been subjected to a power-law adaptation function to simulate octopus cell responses. Model responses are compared to the actual physiological data recorded from octopus neurons. Output of the proposed model can be applied as an excitatory input to model responses of superior paraolivary nucleus neurons located in the superior olivary complex and also in the model of sound localization.

*Key Words*—Octopus cells, acoustic information encoding, neural response simulation, brain modeling

## **Introduction**

Sound is an acoustical pressure which contains two important features, namely, frequency and intensity (Pickles, 2012). In the auditory system of the brain, sound attributes are represented by action potentials (characteristic electrical pulses) of neurons (Dayan and Abbott, 2001). Each cell (neuron) type of the auditory pathway plays a specific role in encoding important features of the sound. The pure tone, the simplest form of sound, has been used in many electrophysiological experiments to investigate how the auditory system of mammals, including human, encodes related information (Carney, 2002). However, since the auditory system is not

linear, responses to the pure tone cannot be simply applied to explain processing of complex sounds (such as speech). Developing a computational model based on existing physiological data could be a helpful approach to test our understandings regarding the ways in which complex sounds are processed through the auditory system. The main aim of this study is to develop a computational model of the responses of the octopus cells in the cochlear nucleus. Octopus cells are very helpful in terms of encoding the precise temporal features of the natural sounds. These neurons occupy a separate region within the posteroventral cochlear nucleus (PVCN) of all mammals (Golding

et al., 1995) and receive inputs from a great number of auditory nerve (AN) fibres. Low input resistance as well as short time constant are the most significant properties of octopus cells (Bal and Oertel, 2007). Moreover, these neurons make one of the major pathways in which acoustic information can be conveyed from the auditory-nerve fibers into the upper levels of the auditory system (Bal and Oertel, 2001 ; Salimi et al., 2017). Two types of physiological responses to pure tones at the characteristic frequency (CF) have been shown for octopus cells based on their post-stimulus time histogram (PSTH) responses. These two types of responses are onset-locker (OL) and onset-ideal (OI) (Godfrey et al., 1975). The OL type has a very precise response at the onset of the stimulus which is followed by a very small sustained activity, while the OI type shows only an onset component. It is important to note that this onset pattern can be observed in response to stimuli with frequencies more than about 2 kHz. In addition to pure tone, responses of octopus neurons to more complex sounds such as sinusoidally amplitude-modulated (SAM) stimuli have also been recorded in the physiological experiments.

Different mechanisms have been suggested to model the response properties of octopus cells in the PVCN. In the study by Cai et al. (2000), the octopus cell was assumed to be sensitive to the rate of change of its membrane potential. The onset response to the pure tone was simulated by activating a low-threshold potassium channel during ramp-up stage of the input current. In another study by Sumner et al. (2009), the onset response of the octopus cells was simulated by auditory-nerve innervations and the dendritic filtering. Although the

above-mentioned models successfully simulated the responses of octopus neurons to the pure tone, the model responses to the SAM stimulus were not evaluated.

A new mechanism, power-law adaptation, has been suggested in this study to simulate the physiological responses of octopus cells to both the pure tone and SAM stimuli. Next section describes the details of the approach used to develop the model of octopus cells in the PVCN. A comparison between the responses of the model and actual physiological data is provided in the Result section, and the final section provides the conclusion of this study.

## Method

The approach applied to develop a model of the physiological responses of octopus cells is discussed in this section. Figure 1 shows the schematic diagram of the proposed model. As discussed earlier, octopus neurons receive their inputs from the auditory-nerve (AN) fibres, and thus the responses of the AN model (Zilany et al., 2009) have been used as an input to the model of the octopus cell. Most of the nonlinearities observed in the recordings of the auditory-nerve fibre such as nonlinear tuning, compression, two-tone suppression, level-dependent phase, and adaptation, were successfully captured by the AN model used in this study (Zilany et al., 2009). The AN model responses were validated against a wide range of actual physiological responses from the experiments, including PSTHs to simple and complex stimuli. The ability of the AN model to replicate the phase-locking property to the envelope of the SAM stimulus is another important aspect of the model used in this study.



Figure 1: A schematic diagram of the model of the octopus neuron in the PVCN. The input to the model is an acoustic stimulus which is passed through the model of the AN fibre. The model AN responses for a range of CFs are weighted and added together before a power-law adaptation function is applied. The final output of the model is the simulated responses of the octopus neuron.

In order to predict the responses of octopus cells, the simulated responses from five auditory-nerve fibres were weighted and added together. The range of CFs for which AN outputs were simulated was set to 2 octaves higher and lower than the CF of the corresponding octopus neuron. Then, the output of this stage [ $r_{AN}(t)$ ] was subjected to a power-law adaptation (PLA) function (Eq. 1). Power-law adaptation is increasingly common in describing the dynamics of biological systems including sensory adaptation. Power-law dynamics can be approximated by a combination of exponential processes with a range of time constants and thus can model the coexistence of multiple time scales in a single adaptive process (Brown and Stein, 1966; Thorson and Biederman-Thorson, 1974; Drew and Abbott, 2006; La Camera et al., 2006). Note that octopus cells in the PVCN are at least a synapse away from the AN fibres, and thus multiple processes (e.g., depletion of “readily releasable” pool, endocytosis, exocytosis, and postsynaptic receptor desensitization) with a range of time constants could contribute to the neural adaptation (Raman et al., 1994; Moser and Beutner, 2000; Spassova et al., 2004). The PLA function was employed in this study to simulate the adaptation process between the AN fibres and the octopus cells. It is worth noting that the power-law dynamics have also been employed to explain complex and diverse adaptation in the synapse between

the inner-hair cell and the auditory nerve (Zilany et al., 2009; Zilany and Carney, 2010). Since the rate cannot be negative, the output of the octopus cell,  $r_{oct}(t)$ , was derived as follows:

$$r_{oct}(t) = \max[0, r_{AN}(t) - I(t)],$$

$$I(t) = \alpha \int_0^t \frac{r(t')}{t-t'+\beta} dt' \quad (1)$$

Applying appropriate weights for the AN model responses and setting both the values of  $a$  and  $\beta$  to  $9 \times 10^{-6}$  (or  $12 \times 10^{-6}$ ) could lead to simulating the OL (or OI) type responses of octopus cells. Responses of the proposed model to the pure tone and sinusoidally amplitude-modulated stimuli were compared to the corresponding physiological responses reported in the literature.

## Results and Discussion

In this section, the responses of the proposed model are compared to the actual data recorded in the relevant physiological experiments. Two types of responses to pure tones as well as responses to the SAM stimulus are considered.

### Octopus cell responses to the pure tone

The model and actual octopus cell responses are illustrated in Figs. 2 and 3. In order to have a reliable comparison, stimulus conditions were matched to those of the respective physiological study. By setting the values of

$a$  (dimensionless) and  $\beta$  ( $s$ ) of the power-law adaptation function to  $9 \times 10^{-6}$ , the proposed model was able to replicate the OL-type responses to the pure tone (Fig. 2). Both the physiological (A) and model (B) responses showed an onset component which was significantly higher than the sustained part. In addition, a very short duration of suppression was observed immediately after the onset component in both the model and physiological responses. Moreover, the sustained component gradually declined as a function of time.

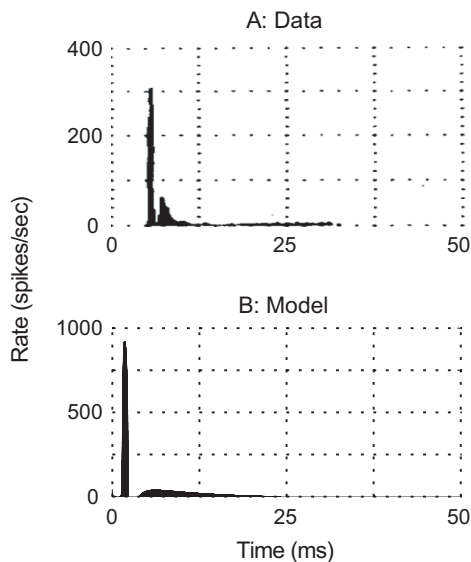


Figure 2: Actual physiological (A) and model (B) responses of an octopus neuron. The input stimulus was a pure tone at CF. The model responses (B) resembled the onset-locker (OL) type of responses recorded in the electrophysiological experiment (A). Stimulus parameters: CF = 9.5 kHz, sound level = 55 dB, duration = 25 ms. Actual data are reproduced from Godfrey et al. (1975).

In order to model the OI type of responses, the values of  $a$  and  $\beta$  had to be increased to  $12 \times 10^{-6}$ . Figure 3 shows the actual (A) as well as model (B) responses of an octopus cell to the pure tone at CF (7.8 kHz), and the duration and level of the stimulus were 25 ms and 55 dB SPL, respectively. It is obvious that both the model and physiological responses showed a remarkable onset component with a zero sustained activity.

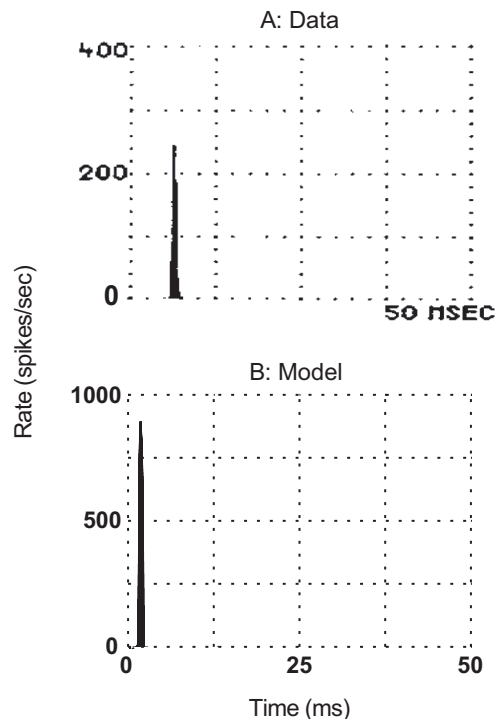


Figure 3: Actual physiological (A) and model (B) responses of an octopus cell to a pure tone. The proposed model was able to simulate the onset-ideal (OI) type of responses, which is consistent with the physiological responses using the same stimulus conditions. Stimulus parameters: CF = 7.8 kHz, sound level = 55 dB SPL, and stimulus duration = 25 ms. Actual data are reproduced from Godfrey et al. (1975).

### Octopus Cell Response to the SAM Stimulus

SAM stimulus can be defined as

$$S(t) = (1 + m \sin(2\pi f_m t)) \times \sin(2\pi f_c t), \quad (2)$$

where  $f_m$  is the modulation frequency,  $f_c$  represents the carrier frequency, and  $m$  determines the modulation depth of the signal.

In order to show the modulation transfer function (MTF) of the octopus neuron, responses to the SAM stimulus were simulated for modulation frequencies ranging from 50 to 2550 Hz. The carrier frequency of the signal was matched to the CF of the unit in the relevant experiment (indicated in Fig. 4). Then, from the model responses, sync-MTFs (synchrony coefficients versus modulation frequencies) and rate-MTFs (rate versus modulation frequencies) were constructed at different sound levels to compare with the corresponding physiological responses from the experiments (Rhode and Greenberg, 1994). The stimulus duration was set to 1 s for simulating model responses which was different from the stimulus duration of the respective physiological study ( $T = 100$  ms). However, this difference did not affect the trend observed in the obtained results. Figure 4 represents the actual and model rate-MTFs in panels A and C, respectively. The sync-MTFs from the actual physiological experiments and model responses are shown in panels B and D, respectively. Note that the MTFs were obtained for the OL unit only.

The rate-MTF of the model responses was typically low-pass or flat in nature, which is consistent with the physiological responses. However, the cut-off frequency of the model rate-MTF was much lower than the cut-off

frequency of the actual responses (~300 Hz versus 1000 Hz). In addition, changes in the rate as a function of the sound intensity showed a different trend between the model and actual responses, which could be attributed to the power-law adaptation function (i.e., parameters) employed in the proposed model. In terms of the sync-MTF, model responses were low-pass in shape for all stimulus levels studied. However, shape of the sync-MTF related to the physiological data was low-pass at lower sound intensities and became band-pass at higher sound levels (around 70 dB SPL).

It is worth-noting that the minority of the octopus cells had a low-pass sync-MTF for all intensities tested (Rhode and Greenberg, 1994). Again, the cut-off frequency of the model sync-MTF was much lower than the cut-off frequency of the physiological sync-MTF. In addition, the cut-off frequency of the model sync-MTF increased with increasing the sound level, whereas in the physiological responses, the cut-off frequency remained relatively constant with the sound level.

### Conclusion

A computational model to simulate the responses of octopus cells is proposed in this study. Responses of the model auditory-nerve fibres were simulated at the first stage of the proposed model. These responses were weighted and summed and then applied as an input to the power-law adaptation function. Setting appropriate parameters for the power-law adaptation function led to simulating the octopus cell responses for a reasonable range of sound intensities and frequencies. The proposed model was able to simulate physiological responses of octopus neurons to both the simple and complex

stimuli. The output of the proposed model can be applied as an input to the model of neurons located at higher levels of the auditory pathway.

**Acknowledgements**

This work was supported by the grant RP016B-13AET from the University of Malaya.

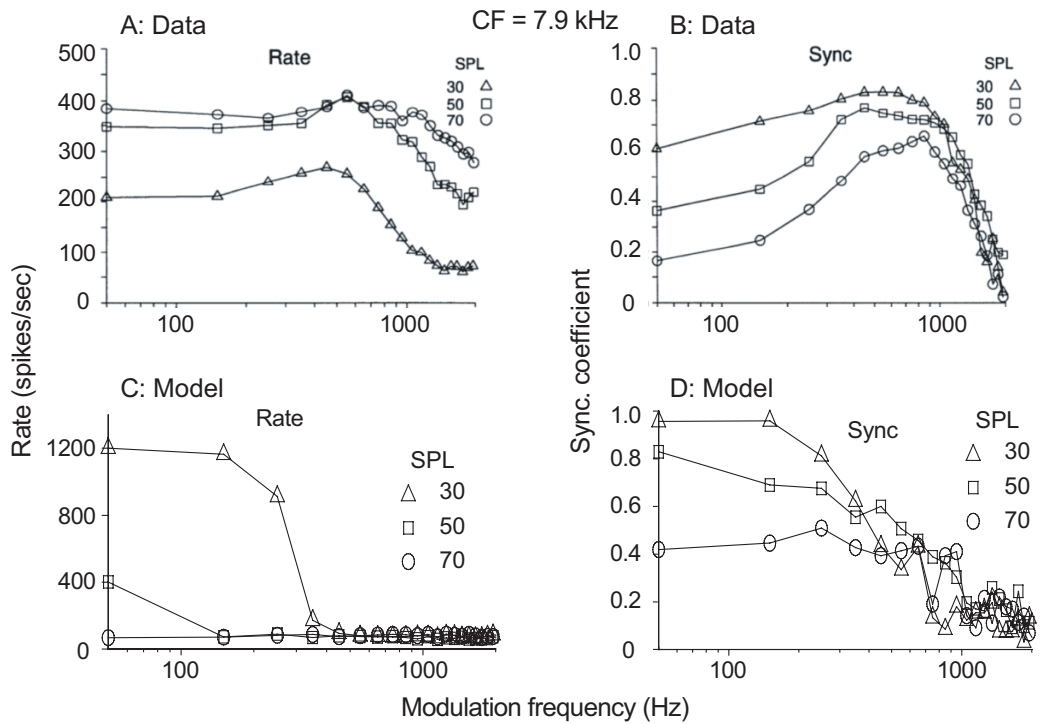


Figure 4: Actual physiological (A and B) and model (C and D) responses to the sinusoidally amplitude-modulated stimuli for three different sound pressure levels (SPLs). The stimulus intensities (SPLs) are indicated in each panel. Panels A and C show discharge rate as a function of modulation frequency, while panels B and D illustrate synchrony coefficient as a function of modulation rate. Generally, the model responses followed the trends observed in the physiological responses. However, model responses were suppressed at the lower modulation frequencies compared to the responses from the physiological data. Actual data are reproduced from Rhode and Greenberg (1994).

## References

- Bal R., Oertel D. (2001) Potassium currents in octopus cells of the mammalian cochlear nucleus. *Journal of Neurophysiology* 86: 2299-2311.
- Bal R., Oertel D. (2007) Voltage-activated calcium currents in octopus cells of the mouse cochlear nucleus. *Journal of the Association for Research in Otolaryngology* 8: 509-521.
- Brown M., Stein R. (1966) Quantitative studies on the slowly adapting stretch receptor of the crayfish. *Kybernetik* 3: 175-185.
- Cai Y., McGee J., Walsh EJ (2000) Contributions of ion conductances to the onset responses of octopus cells in the ventral cochlear nucleus: simulation results. *Journal of Neurophysiology* 83: 301-314.
- Carney L.H. (2002) Neural Basis of Audition. *Stevens' Handbook of Experimental Psychology*. (3<sup>rd</sup> ed.)
- Dayan P., Abbott L.F. (2001) *Theoretical Neuroscience*: Cambridge, MA: MIT Press.
- Drew P.J., Abbott L.F. (2006) Models and properties of power-law adaptation in neural systems. *Journal of Neurophysiology* 96: 826-833.
- Godfrey D.A., Kiang N., Norris B.E. (1975) Single unit activity in the posteroventral cochlear nucleus of the cat. *Journal of Comparative Neurology* 162: 247-268.
- Golding N.L., Robertson D., Oertel D. (1995) Recordings from slices indicate that octopus cells of the cochlear nucleus detect coincident firing of auditory nerve fibers with temporal precision. *Journal of Neuroscience* 15: 3138-3153.
- La Camera G., Rauch A., Thurbon D., Lüscher H.-R., Senn W., Fusi S. (2006) Multiple time scales of temporal response in pyramidal and fast spiking cortical neurons. *Journal of Neurophysiology* 96: 3448-3464.
- Moser T., Beutner D. (2000) Kinetics of exocytosis and endocytosis at the cochlear inner hair cell afferent synapse of the mouse. *Proceedings of the National Academy of Sciences* 97: 883-888.
- Pickles J.O. (2012) *An Introduction to the Physiology of Hearing*. (4<sup>th</sup> ed.) Emerald Group.
- Raman I., Zhang S., Trussell L. (1994) Pathway-specific variants of AMPA receptors and their contribution to neuronal signaling. *Journal of Neuroscience* 14: 4998-5010.
- Rhode W.S., Greenberg S. (1994) Encoding of amplitude modulation in the cochlear nucleus of the cat. *Journal of Neurophysiology* 71: 1797-1825.
- Salimi N., Zilany M.S.A., Carney L.H. (2017) Modeling responses in the superior paraolivary nucleus: implications for forward masking in the inferior colliculus. *Journal of the Association for Research in Otolaryngology* 18: 441-456.
- Spassova M.A., Avissar M., Furman A.C., Crumling M.A., Saunders J.C., Parsons T.D. (2004) Evidence that rapid vesicle replenishment of the synaptic ribbon mediates recovery from short-term adaptation at the hair cell afferent synapse. *Journal of the Association for Research in Otolaryngology* 5: 376-390.
- Sumner C.J., Meddis R., Winter I.M. (2009) The role of auditory nerve innervation and dendritic filtering in shaping onset responses in the ventral cochlear nucleus. *Brain Research* 1247: 221-234.
- Thorson J., Biederman-Thorson M. (1974) Distributed relaxation processes in sensory adaptation. *Science* 183: 161-172.
- Zilany M.S., Carney L.H. (2010) Power-law dynamics in an auditory-nerve model can account for neural adaptation to sound-level statistics. *Journal of Neuroscience* 30: 10380-10390.
- Zilany M.S., Bruce I.C., Nelson P.C., Carney L.H. (2009) A phenomenological model of the synapse between the inner hair cell and auditory nerve: long-term adaptation with power-law dynamics. *Journal of the Acoustical Society of America* 126: 2390-2412.

