Oscillating Electrical Signal Propagation along Microtubules

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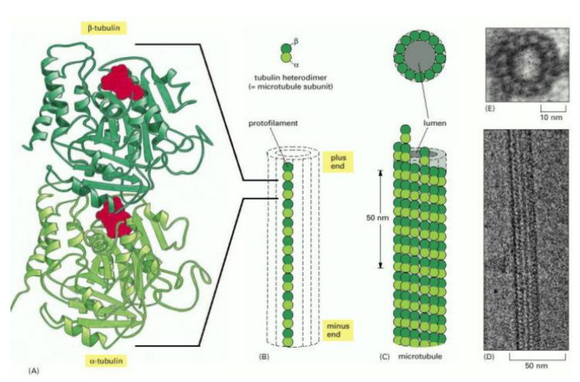
Abstract

Microtubules (MTs) are tubular cytoskeletal polymers with a regular longitudinal arrangement of nanopores connecting the outer and inner surfaces. A compact and tiny "skin-like" ionic aqueous layer formed between the surrounding fluid and each surface of the filament gives these MTs an extraordinary ability to sustain ionic conductance to transmit and amplify oscillatory electric signals, the frequency of which is similar to the one measured in electrical activities of the brain. This study introduces a novel coupled electrical circuit transmission line model for isolated MTs to investigate the molecular mechanisms underlying the axial transmission and amplification of the oscillating signals. Each transmission line represents the ionic current flowing on the outer and inner surfaces of the MT. At the same time, ionic nanopore currents cause the transmission lines to be coupled through nanopores. Our preliminary results revealed axial oscillating ionic currents as traveling localized ionic waves. Meanwhile, the energetic interchange between the outer and inner ionic currents produces oscillations controlled by the nanopore conducting properties. These features provide the cytoskeletal matrix with a novel mechanism for neuron information processing.

Microtubule—a hollow cylinder



- α-tubulin and β-tubulin form a dimer
- Dimers produce protofilaments
- 13 protofilaments form the MT sheet
- MT sheet folds into a hollow cylinder

Fig: Microtubule structure [1].

Microtubules transmit and amplify electric signals

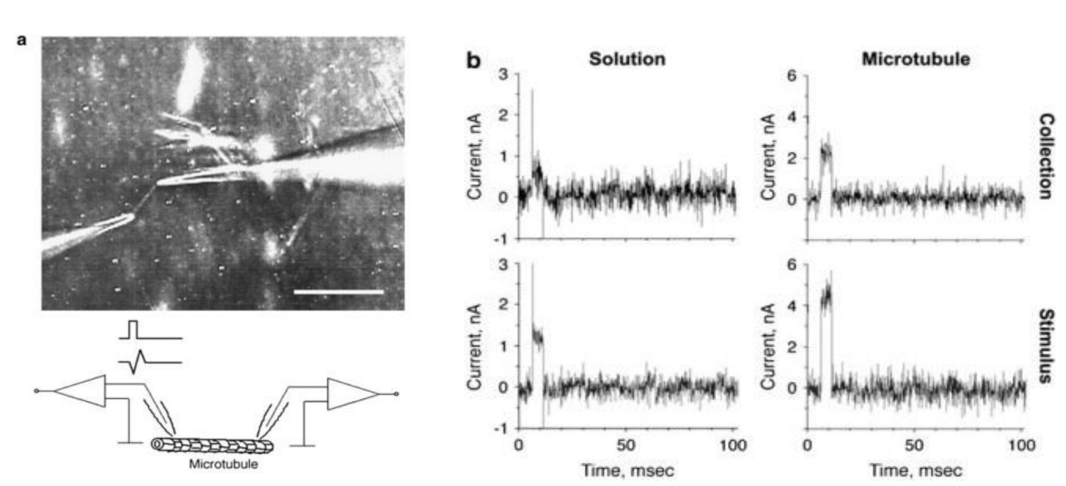


Fig: Currents were higher after attachment to an MT, compared to saline solution [2].

Microtubules produce electrical oscillations

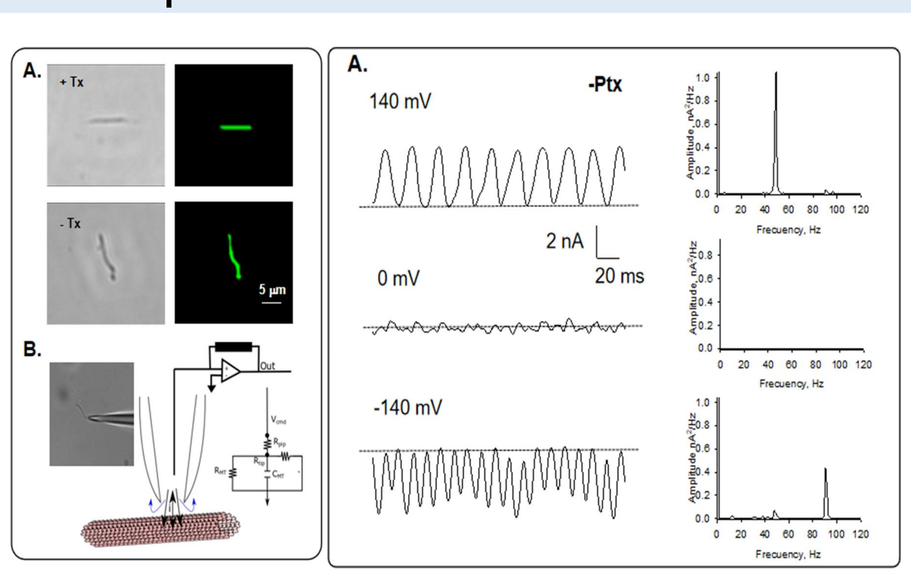


Fig: Current fluctuations at different holding potentials of an isolated MT in the absence of Paclitaxel (−Ptx)[3].

Previous works

- Single transmission line models are unable to predict electrical signal oscillation.
- Transmission line models for MT do not include the lumen transmission line explicitly.
- Coupled transmission line and coupled soliton was studied in electrical engineering. One soliton increases and accelerates while the other decreases and decelerates and take turns (leapfrogging). Leapfrogging solitons were studied in electrical engineering [4].

Our hypotheses

- We consider counterion condensation on outer and inner surface of MT forming two transmission lines connected (coupled) through the nanopores.
- Both surfaces (i.e. both transmission lines) have their own capacitive and resistive properties.
- Lumen transmission line is required to get soliton oscillation.
- Thus, two localized solitons travel along MT.
- Oscillation happens due to energy exchange between the solitons through pores.
- We consider the pore as the interacting mechanism between the transmission lines.

A novel coupled transmission line model for microtubule

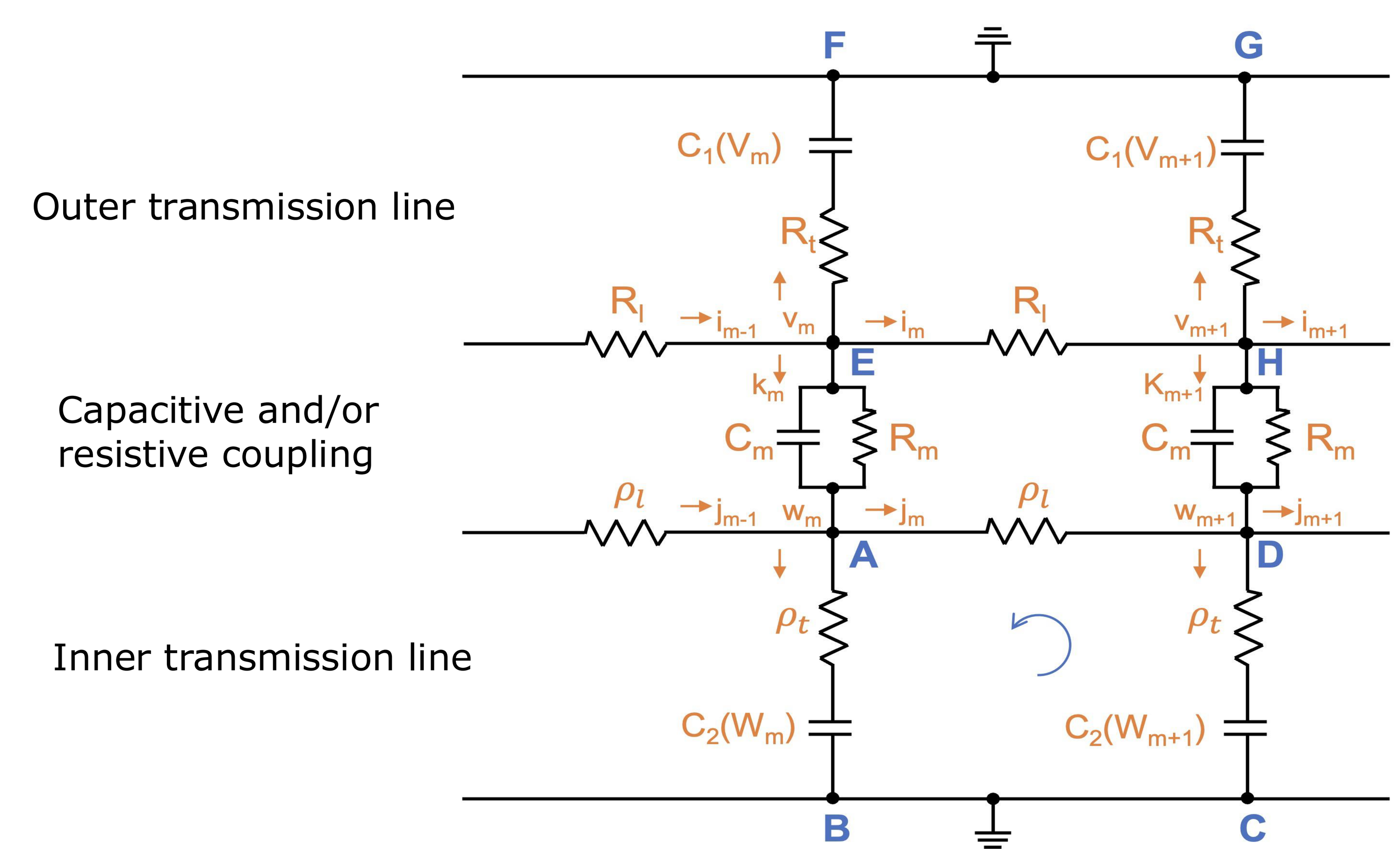


Fig: Two coupled transmission line model for microtubule. Condensed ions on outer and inner walls of microtubules form transmission lines. The transmission lines are connected by conductance representing pores connecting two surfaces of microtubule.

- Transmission line equations are perturbed coupled KdV equations.

$$\frac{\partial \Psi}{\partial \tau} - 6\Psi\frac{\partial \Psi}{\partial \xi} + \frac{\partial^3 \Psi}{\partial \xi^3} = -M_1\frac{\partial \Psi}{\partial \xi} + M_2\frac{\partial \Phi}{\partial \xi} - N_1\Psi - N_2\Phi + \nu_1\frac{\partial^2 \Psi}{\partial \xi^2} - F_1\frac{\partial^3 \Psi}{\partial \xi^3}$$

$$\frac{\partial \Phi}{\partial \tau} - 6\Phi\frac{\partial \Phi}{\partial \xi} + \frac{\partial^3 \Phi}{\partial \xi^3} = -M_3\frac{\partial \Phi}{\partial \xi} + M_4\frac{\partial \Psi}{\partial \xi} - N_3\Phi - N_4\Psi + \nu_2\frac{\partial^2 \Phi}{\partial \xi^2} - F_2\frac{\partial^3 \Phi}{\partial \xi^3}$$

Results

- We ignored the terms in ν_1 and ν_2 and evaluated the coefficients in the coupled equations .
- The coefficients are derived from MT transmission line parameters.

parameter	value
N1	0.00411754
N2	0.00192422
N3	0.00742433
N4	0.00370005
M1	−1.89512
M2	1.0041
M3	−1.97535
M4	2.1499
F1	−0.0789631
F2	−0.0823061

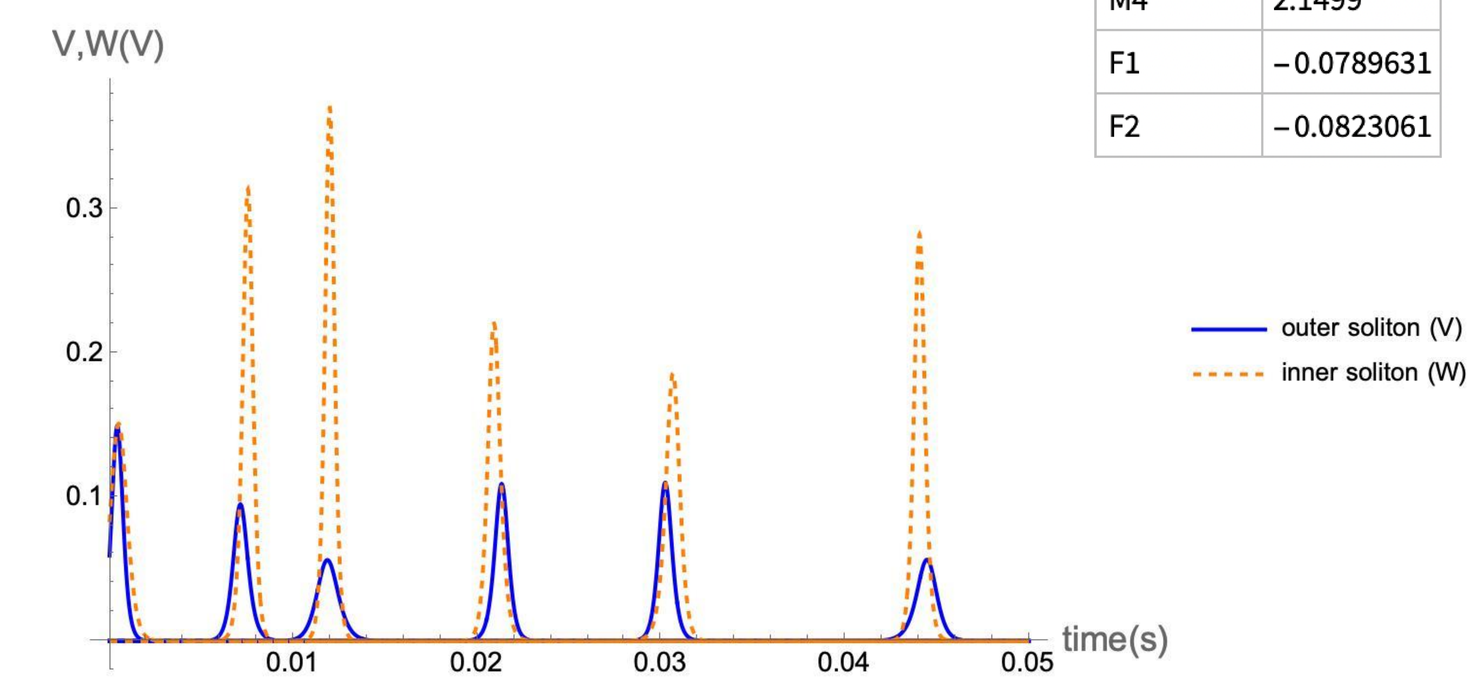


Fig: Leapfrogging solitons

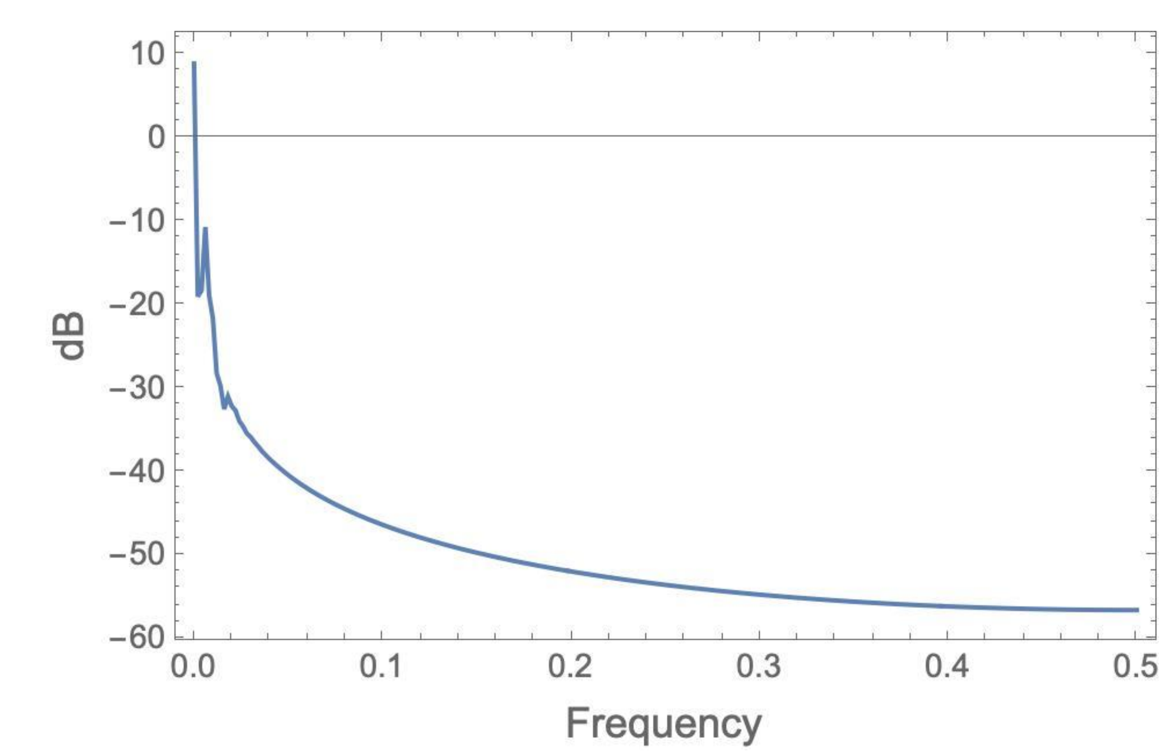


Fig: From periodogram the frequency is 39 Hz.

Ongoing research and future direction

- We are evaluating coefficients of transmission line equations from the molecular structure and biological environment of microtubule.
- In future, we want to extend the model for physiological and pathological conditions of microtubules.

References

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