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Field Model of Plasma Shock Wave Interaction with Cell Membranes: A Multiscale Framework for Biomedical Applications

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ABSTRACT

Introduction: Plasma treatments require a precise understanding of the mechanical energy transfer of shock waves to the cell membrane. In this study, the membrane was modeled as a continuous field $\phi(x,t)$ with bending energy, surface tension, and viscous damping, and the shock wave was introduced into the Lagrangian of the system as an external source $J(x,t)$. The frequency domain response was calculated using Green's function. The results showed that the energy absorption strongly depends on the spectral overlap of the pulse with the natural modes of the membrane. A small temperature increase of $\Delta T \approx 0.64K$ causes a 30–35% decrease in the bending stiffness (κ) and surface tension (σ) and significantly lowers the reversible permeability threshold. This mechanism provides, for the first time, a clear physical explanation for plasma bioselectivity (stimulation versus degradation).

Materials and Methods: The cell membrane was modeled as a vertical displacement field, $\phi(x,t)$. The basic Lagrangian consists of three components: bending energy, surface tension, and surface mass: $L_0 = \int d^2x[\frac{\rho_m}{2}(\partial_t\phi)^2 - \frac{\kappa}{2}(\nabla^2\phi)^2 - \frac{\sigma}{2}(\nabla\phi)^2]$ Natural mode dispersion relation: $\omega_k^2 = \frac{\sigma k^2+\kappa k^4}{\rho_m}$ The shock wave was introduced as an external source $J(x,t) = Af(x)\delta(t-t_s)$. The final equation of motion was obtained as a damped flexural-tensile wave: $J(x,t) = \kappa\nabla^4\phi + \sigma\nabla^2\phi + \rho_m\partial_t^2\phi + \gamma\partial_t\phi$ By the Fourier transform in wave vector space, each k-mode was converted into a damped harmonic oscillator. The energy absorbed in each mode was calculated using the Green's function in the frequency domain: $E_k \propto \frac{1}{\rho_m^2}\left|\int J_k(t)e^{i(\omega_{k+}i\Gamma_k)t}dt\right|^2 \frac{1}{\omega_k}$ Physical parameters were selected from reliable biophysical sources ($\kappa = 20-40K_{\beta T}, \sigma \approx 10^{-3}-10^{-5}N/m, \rho_m \approx 10Kg/m^2$).

Results and Discussion: Plasma shock waves transfer mechanical energy to cell membranes, but existing models overlook membrane vibrational dynamics. Here, we present a theoretical field model where the membrane is described as a continuum field $\phi(x,t)$ with bending rigidity (κ), surface tension (σ), and damping, driven by a spatiotemporal shock source $J(x,t)$. Simulations of the frequency-domain response reveal that energy absorption peaks within wavenumbers ($k \approx 10^5 - 10^6 m^{-1}$), corresponding to natural flexural modes. A mild temperature rise ($\Delta T \approx 0.64K$) softens κ and σ by 30–35%, dramatically lowering the threshold for reversible permeabilization. The simulated absorbed areal energy ($3.18\times 10^{-2}J/m^2$) remains below the rupture limit, placing the membrane in a mechanically activated, non-destructive state. This theoretical framework resolves the selectivity paradox in plasma medicine by linking spectral overlap and thermal softening to tunable outcomes—stimulation or damage—based on pulse parameters.

Conclusion: The highest energy absorption occurred in the range $k \approx 10^5 - 10^6 m^{-1}$. The absorbed surface energy was $3.18\times 10^{-2}J/m^2$ and $\Delta T = 0.64K$, which is in the region of mechanical-thermal activation and below the rupture threshold ($E_{crit} \approx 10^{-1} - 10^{-3}J/m^2$). This leads to increased thermomechanical fluctuations, reversible permeability, and facilitated drug delivery without structural damage. The present model enables the design of optimal plasma pulses for electroporation, wound healing, and selective cancer treatment applications, and resolves the paradox of selectivity of plasma biological effects by combining Mody resonance and thermal membrane softening.

Keywords: Chemotherapy, Chondrosarcoma, Drug synergism, Plasma gases

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