Engineering Light-Responsive Liposomal Complexes: Gold Nanorods as Photothermal Triggers for Targeted Drug Release

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The rational design of nanoparticle-based drug delivery systems requires a mechanistic understanding of how nanoparticle geometry and surface chemistry modulate lipid membrane behavior. As the structural and functional backbone of liposomal nanocarriers, lipid bilayers are highly sensitive to incorporated nanomaterials, and characterizing these interactions is essential for predicting therapeutic performance and biocompatibility. Here, we investigate the thermodynamic and photothermal effects of PEG-coated gold nanorods (AuNRs) on SOPC-based liposomal bilayers, with the aim of establishing their potential as controllable agents in light-responsive nanomedical systems.

PEG-AuNRs, used in the study, exhibit a rod-like morphology with an average length of 55 ± 18 nm and width of 15 ± 5 nm (aspect ratio ~4.1), consistent with a pronounced longitudinal surface plasmon resonance in the visible range. Dynamic light scattering confirmed a hydrodynamic diameter of 60-90 nm and a zeta potential of -26 mV, indicating moderate colloidal stability. A multitechnique approach combining ATR-FTIR spectroscopy, differential scanning calorimetry (DSC), and laser irradiation at 343, 515, and 1030 nm was employed to assess AuNR-membrane interactions across thermodynamic and optical dimensions.

DSC measurements reveal that AuNR incorporation at 0.5%, 1%, and 2.5% produces a non-monotonic, concentration-dependent perturbation of bilayer thermodynamics, with heating enthalpies of 0.269, 0.371, and 0.326 J/g respectively, indicative of a complex membrane interaction distinct from simple fluidization. Photothermal characterization in physiological medium demonstrates efficient light-to-heat conversion with strong wavelength and power density dependence: 515 nm irradiation at 0.2 W cm^{-2} yielded a maximum temperature increase of ~38.9 °C within 10 minutes, while 1030 nm excitation produced only modest heating (~7.2 °C), identifying the visible range as the optimal spectral window for AuNR-mediated thermal actuation. To summarize, these findings support AuNRs as high-performance photothermal agents capable of controllably modulating lipid membrane properties, with promising implications for thermosensitive liposomal drug delivery platforms.

Keywords:
nanoparticle membrane interactions; gold nanorods; photothermal therapy; light-to-heat conversion; laser irradiation

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