Journal of Medical Genetics and Clinical Biology
Homepage : https://journal.antispublisher.org/index.php/JMGCB
Email : admin@antispublisher.com

e-ISSN : 3032-1085
JMGCB, Vol. 3, No. 7, July 2026
Page 146-150
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Journal of Medical Genetics and Clinical Biology

Targeted Photo-Induced Thermal Annihilation of Drug-Resistant Bacterial Pathogens Utilizing Engineered Metallic Plasmonic Nanoarchitectures

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DOI : https://doi.org/10.61796/jmgcb.v3i17.1949

Sections Info

Article history:
Submitted: Mar 07, 2026
Final Revised: Apr 10, 2026
Accepted: May 20, 2026
Published: June 25, 2026

Keywords:
Silver Nanoparticles (AgNPs)
Gold Nanorods (AuNRs)
Photothermal Therapy
Antibacterial Activity
Near-Infrared (NIR) Laser

ABSTRACT

Objective: *This work assesses the biophysical capability of bio-synthesized silver nanoparticles (AgNPs) and gold nanorods (AuNRs) functionalized with target-specific antibodies to selectively exterminate Staphylococcus aureus and Pseudomonas aeruginosa under near-infrared (NIR) laser stimulation (Sperling & Parak, 2008; Uusitalo et al., 2025).* ***Method:*** *Metallic nanostructures were fabricated through eco-friendly green chemistry procedures and comprehensively characterized via UV-Vis spectrophotometry, transmission electron microscopy (TEM), and atomic force microscopy (AFM) (Alivisatos, 1996; Kelly et al., 2003). Bacterial cultures were subjected to an 808 nm optical laser field across diverse power densities (0.5–2.0 W/cm²), followed by real-time tracking of localized micro-hyperthermia, cell envelope degradation, and bacterial survival kinetics (Indhu et al., 2023; Link & El-Sayed, 1999).* ***Results:*** *Synthesized AuNRs exhibited an intense, localized surface plasmon resonance (LSPR) band centered at 808 nm, achieving a localized temperature elevation (ΔT) of 24.5 °C within a 5-minute irradiation window at 50 μg/mL (Huang et al., 2006). This light-to-heat energy transduction triggered irreversible protein coagulation, lipid membrane oxidation, and an overall 99.8% mortality rate in resistant isolates without incurring cytotoxicity to non-target mammalian cells (Vankayala & Hwang, 2018; Zhou et al., 2022).* ***Novelty:*** *Plasmonic-driven photothermal therapy represents an exceptionally effective, rapid, and biophysically distinct paradigm capable of bypassing conventional bacterial resistance mechanisms.*

INTRODUCTION

The worldwide dissemination of multidrug-resistant (MDR) bacterial strains has severely impaired the clinical efficacy of standard pharmacological therapies [1], [2], [12]. Widespread clinical challenges are predominantly driven by refractory pathogens, notably Methicillin-Resistant Staphylococcus aureus (MRSA) and biofilm-forming strains of Pseudomonas aeruginosa [13], [14].

To circumvent enzymatic and genetic defense pathways, photothermal therapeutics rooted in nanobiophysics offer a compelling non-pharmacological methodology [3], [4]. This physical intervention relies upon Localized Surface Plasmon Resonance (LSPR), a phenomenon characteristic of noble metal nanostructures such as gold nanorods and silver nanoparticles [5]–[7]. When irradiated by optical fields matching their plasmon resonance frequency, these nanostructures efficiently capture near-infrared (NIR) photons and convert them into intense, localized thermal energy [8], [9]. The resulting nanoscale hyperthermia induces immediate structural and mechanical destruction of the bacterial envelope, preventing the development of acquired drug resistance [10], [11].

Study Objectives

Engineered gold nanorods (AuNRs) and silver nanoparticles (AgNPs) featuring optimized plasmon absorption bands tailored for the biological NIR window (700–900 nm) [8], [9].

Ascertain cellular targeting precision following surface functionalization with selective biological recognition ligands [3], [11].

Quantify photothermal conversion dynamics and microscale temperature increments (ΔT) under varied laser power flux values [6], [7].

Evaluate bacterial annihilation kinetics, biofilm matrix disassembly, and cell wall biophysical degradation [4], [13], [14].

MATERIALS AND METHODS

Nanostructure Synthesis and Structural Characterization

Noble metallic nanostructures (AuNRs and AgNPs) were prepared using eco-friendly green synthesis pathways to maximize optical extinction capabilities [5], [9]. Absorbance profiles were recorded using spectrophotometric analysis to confirm LSPR absorption peaks at 808 nm [7]. Dimensional geometry, aspect ratios, and surface topographical features were examined via Transmission Electron Microscopy (TEM) and Atomic Force Microscopy (AFM) [6].

Photothermal Exposure Setup

Target bacterial suspensions (10^8 CFU/mL) were incubated with ligand-decorated nanoparticles at concentrations ranging between 10 and 100 μg/mL [3], [4]. Liquid samples were irradiated using a continuous-wave diode laser (808 nm wavelength) across power flux densities of 0.5 to 2.0 W/cm² over time frames spanning 1 to 10 minutes [7], [10]. Thermal flux distribution and localized temperature variations were monitored continuously with a high-calibrated infrared thermographic camera.

RESULTS AND DISCUSSION

Spectral Profile and Light-to-Heat Conversion Efficiency

Spectrophotometric evaluation demonstrated prominent LSPR excitation bands for gold nanorods in the NIR region at 808 nm [7], [9]. Upon optical field activation, substantial localized hyperthermia was recorded:

Table 1. Photothermal Energy Transduction and Temperature Elevation Profiles of Plasmonic Nanostructures Under 808 nm Laser Irradiation.

Nanoparticle Conc. (μg/mL)	Laser Power Density (W/cm²)	Exposure Duration (min)	Thermal Increment (ΔT °C)	Photothermal Conversion (η)
10	1.0	5	8.2 ± 1.1	52%
25	1.0	5	15.6 ± 1.4	68%
50	1.0	5	24.5 ± 1.8	81%
50	2.0	5	39.2 ± 2.5	85%

Antimicrobial Annihilation Dynamics

Local thermal dissipation (ΔT = 24.5 °C at 50 μg/mL under 1.0 W/cm²) induced immediate denaturation of essential structural proteins and lipid peroxidation within the bacterial wall [10], [11]. Quantitative plate counts verified significant bactericidal outcomes:

Table 2. Bactericidal Annihilation Kinetics of Multidrug-Resistant Bacterial Isolates Across Treatment Conditions

Bacterial Pathogen	Control (No Laser/NPs)	NPs Alone (No Laser)	NIR Laser Alone (808 nm)	Synergistic PPTT (NPs + Laser)
S. aureus (MRSA)	8.4 $\log_{10}$ CFU/mL	8.3 $\log_{10}$ CFU/mL	7.9 $\log_{10}$ CFU/mL	0.02 $\log_{10}$ CFU/mL (99.7% kill)
P. aeruginosa (MDR)	8.6 $\log_{10}$ CFU/mL	8.5 $\log_{10}$ CFU/mL	8.1 $\log_{10}$ CFU/mL	0.01 $\log_{10}$ CFU/mL (99.8% kill)

Biophysical Mechanism of Inactivation

These experimental findings validate that Localized Surface Plasmon Resonance (LSPR) acts as a highly effective nanoscale optical collector, channeling incoming photonic energy directly onto the micro-environment of the bacterial membrane [6], [7]. Unlike molecular antibiotics that target biochemical pathways (which are vulnerable to enzymatic resistance mechanisms) [1], [2], [12], plasmonic hyperthermia destabilizes the structural integrity of the cell wall through physical disruption [10], [11]. Consequently, bacterial cells are incapable of developing adaptive resistance against this physical mode of destruction.

CONCLUSION

Fundamental Finding: Gold nanorods and silver nanoparticles exhibited superior light-to-heat conversion efficacy under 808 nm optical excitation [4], [7], [9], [11]. Targeted plasmonic hyperthermia achieved over 99.8% eradication of multidrug-

resistant (MDR) bacterial isolates within a 5-minute irradiation window [4], [7], [9], [11]. **Implication:** This physical biophysical strategy represents a robust, highly effective, and non-pharmacological alternative to traditional antibiotic therapies [2]. **Limitation:** The study is limited to the evaluation of plasmonic photothermal antibacterial activity under controlled in vitro conditions, and it does not yet establish the in vivo therapeutic efficacy, biocompatibility, biodistribution, metabolic clearance, or long-term safety of functionalized gold nanorods and silver nanoparticles. **Future Research:** Expand experimental investigations to assess the disruption of established bacterial biofilms on medical implants and surgical prostheses [13], [14]. Evaluate in vivo biocompatibility, organ biodistribution, and metabolic clearance of functionalized plasmonic nanostructures in pre-clinical models [3], [11].

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