

Review Article	Pak-Euro Journal of Medical and Life Sciences
DOI: 10.31580/pjmls.v8i2.3367	Copy right © All rights are reserved by Corresponding Author
VoL 8 No. 2, 2025: pp. 471-480	
www.readersinsight.net/pjmls	Revised: June 18, 2025 Accepted: June 26, 2025
Submission: April 22, 2025	Published Online: June 30, 2025

NANO-BIOTECHNOLOGY AND ITS APPLICATIONS: A REVIEW

Sana Ullah^{1*}, Hammad Afzal Kayani¹, Muhammad Zubair², Rabya Fatima³, Sheeba Naz⁴, Fazal Haq³, Zafer Hussain³

¹Department of Biosciences, Shaheed Zulfikar Ali Bhutto Institute of Science and Technology (SZABIST), Karachi, Pakistan

²Kausar Abdulla Malik School of Life Sciences, Forman Christian College, Lahore, Pakistan

³Centre of Excellence in Science & Applied Technologies (CESAT), Karachi, Pakistan

⁴Dow College of Biotechnology, Dow University of Health Sciences (DUHS), Karachi, Pakistan

*Correspondence author: Sana Ullah. E. mail: sbadeni1980@gmail.com



Abstract

Nanotechnology has emerged as a transformative field in medicine, enabling the design of nanoscale systems for diagnostics, imaging, and therapy. Among these, gold nanoparticles (AuNPs) have attracted significant attention owing to their tunable size (1–100 nm), inert nature, ease of synthesis, and unique optical properties that have been recognized since their use in ancient artwork. In recent years, AuNPs have demonstrated broad biomedical applications, including photothermal therapy, targeted drug delivery, antiviral strategies, early detection of cardiovascular disorders, cancer diagnosis, kidney disease monitoring, bioimaging, and biosensing. Their surfaces can be functionalized with peptides, antibodies, or polymers to achieve selective cellular targeting through mechanisms such as the enhanced permeability and retention (EPR) effect and receptor-mediated endocytosis. They can be used for other applications with different properties as well by changing the size and chemistry of the gold nanoparticles. The working of gold nanoparticles is first checked *in vitro* and then *in vivo* using animal models. Despite these advantages, challenges remain, including dose-dependent cytotoxicity, stability concerns, and regulatory barriers that limit large-scale clinical translation. Continued research focusing on surface modification, synthesis, and immune evasion strategies is expected to further expand the therapeutic and diagnostic potential of gold nanoparticles.

Keywords: Biomedical applications, Biosensing, Drug delivery, Gold nanoparticles (AuNPs), Photothermal therapy

INTRODUCTION

Nanotechnology is the emerging field now a days and soon we are going to find ourselves immersed in this technology. Nano shows one billionth of something and this technology allows to create and manipulate particles on a nanoscale. Nobody knows what is going to come of it but it is going to revolutionize our way of living. Nanotechnology as its name indicates it's a technology that deals with very tiny particles smaller than bread crumbs. These particles have two or more dimensions in the range of 1-100nm size scale and are known as nanoparticles. This technology basically uses particles that are between 1nm scales to 100nm scale or even less. Nano particles are of great interest during these days not just because of their reduced dimensions but because of their role in forming complex nanostructures and many applications on the health side as well (1-3). In a 2015 study, electrospun nanofiber scaffolds coated with gold nanoparticles were investigated for spinal cord repair. While conventional 3D neuronal networks primarily promoted neurite branching without sufficient axonal elongation, the gold nanoparticle-coated scaffolds supported neuronal differentiation and favored axonal extension with reduced branching. These findings suggested the potential of AuNP-modified scaffolds for repairing spinal cord and other neuronal tissues (4).

Gold nanoparticles have also been explored as real-time cellular probes for tracking bone marrow mesenchymal stem cells (BMSCs) during bone marrow regeneration. In a recent study, dual-energy computed tomography (DECT) was employed, where gold nanoparticles were surface-modified with DNA Transfectin 3000 and a silica layer to enhance cellular uptake and biocompatibility. The nanoparticles were



efficiently internalized by BMSCs, with uptake remaining stable for at least 14 days without affecting cell viability or function. These findings highlight the potential of gold nanoparticles as non-invasive probes for monitoring stem cell-based bone marrow regeneration (5).

In 2018, researchers at the Technion–Israel Institute of Technology developed a novel NIR-triggered drug delivery system using a polymer matrix embedded with gold nanoparticles and the therapeutic agent. Upon exposure to near-infrared (NIR) light, the gold nanoparticles absorb energy, generating localized heat that melts the surrounding polymer and triggers drug release. Importantly, this system employs NIR light to ensure deep tissue penetration without harming healthy cells, and utilizes materials that are FDA-approved, moving the technology closer to clinical application (6).

Scientists say that using of polymer or this new method could be used in future for holding tissues during surgical procedures, for sealing of internal and external injuries and as “biodegradable scaffolds” for the development of transplant organs (6).

A 2018 study demonstrated that programmed cell death is essential for eliminating unwanted, aged, or diseased cells, and highlighted the role of nanoparticle physicochemical properties as regulators of apoptosis. Gold nanoparticles (AuNPs) of different sizes (e. g: 3, 5, 13, 15, and 45 nm) were introduced into rabbit articular chondrocytes, human peripheral blood lymphocytes, and murine macrophages. Notably, 13–15 nm AuNPs induced significant apoptosis, whereas 3 and 45 nm particles showed negligible effects, and 5 nm particles triggered apoptosis only at higher concentrations. In addition to size, nanoparticle shape also influenced apoptosis: hexagonal AuNPs induced higher levels of reactive oxygen species and apoptosis compared to triangular and spherical forms. These findings underscore the importance of AuNP size and shape in modulating apoptosis, offering valuable insights for designing nanomedicines to target diseases where controlled cell death is crucial (7).

A recent study demonstrated a gold nanoparticle-based approach for rapid, sensitive, and cost-effective isolation and identification of specific cells from heterogeneous populations. Gold nanoparticles functionalized with PEG and hyaluronic acid (HA) targeted CD44-expressing cells, producing a detectable color change via receptor–ligand interaction. This method offers a promising diagnostic tool, such as in cancer cell enumeration, and can be adapted for detecting other receptors, broadening applications in medicine and diagnostics (8).

The scale of things below shows a comparison between the natural nanoparticles and manmade nanoparticles so small to be seen with naked eye and require a high-resolution microscope to be seen. This scale was illustrated by the U.S. Department of Energy to demonstrate the nanoscale dimensions of nanoparticles (2).

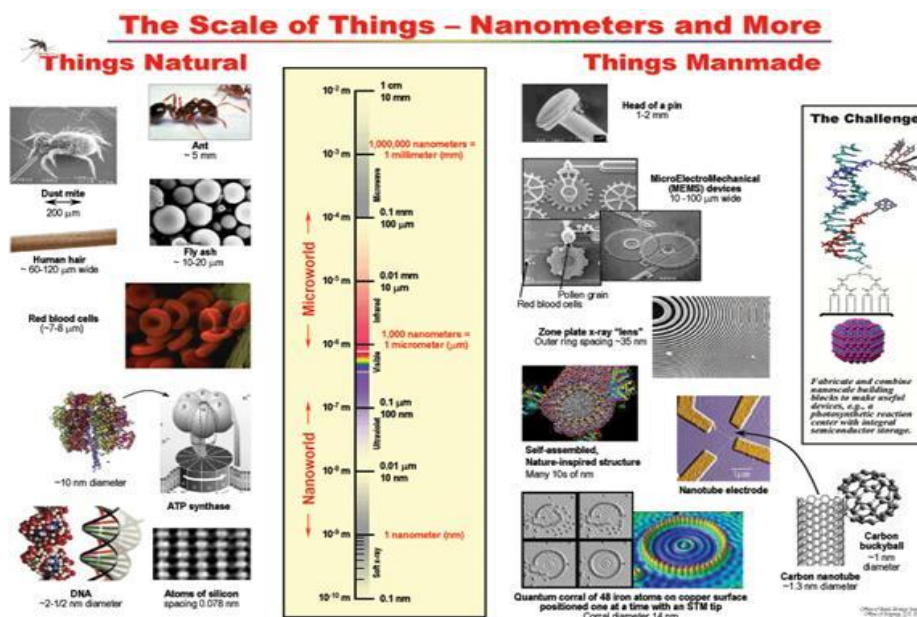


Fig. 1. The scale of things, a way to show how small nanoparticles are (Figure adapted from Roy 2021)

The concept of nanomaterials is not new, historical evidence shows that the Romans created the famous Lycurgus cup, in which the incorporation of metals such as gold and silver at nanometric dimensions produced unique optical effects, appearing red when illuminated from insight and green when viewed externally. This cup was a luxury item made by Romans around 300 AD. It showed red and green light when lit from behind and front respectively (Fig. 2).



Fig. 2. Lycurgus cup infused with nanoparticles (Figure adapted from Alaqad & Saleh 2016)

GOLD NANOPARTICLES (AuNPs)

Gold is a precious metal that is used in making coins, jewelry and in dentistry. It does not corrode and tarnish as it is inert and good conductor of heat and electricity. The optical properties of gold nanoparticles help to absorb and scatter light with amazing proficiency which further can be tuned up by changing the particle size and shape. Gold particles can be coated with polymers and biological molecules due to their “versatile surface chemistry” thus making its use in many areas (4).

The first gold nanoparticle was made by Michael Faraday in 1857. For century’s people used gold just for their exciting colors produced upon interaction of gold with visible light but then in 1850s scientists started detail study of gold properties. Gold nanoparticles now days have various applications on the health side as well. They are safe and good option for doctors to use them in therapeutics, medical treatments, diagnostics and targeted drug delivery purposes as they have not shown any harmful effects and no or less toxic effects as compared to the other metals like platinum which has shown toxic effects and due to their large surface area and high electron conductivity they are widely used in biomedical and biotechnology field (4, 5)

SHAPES OF GOLD NANOPARTICLES

The shape of gold nanoparticles do matter alot based on the type of treatment or their use in various applications. Following are some shapes that are and can be used in many applications to increase the effectiveness of the treatment or method.

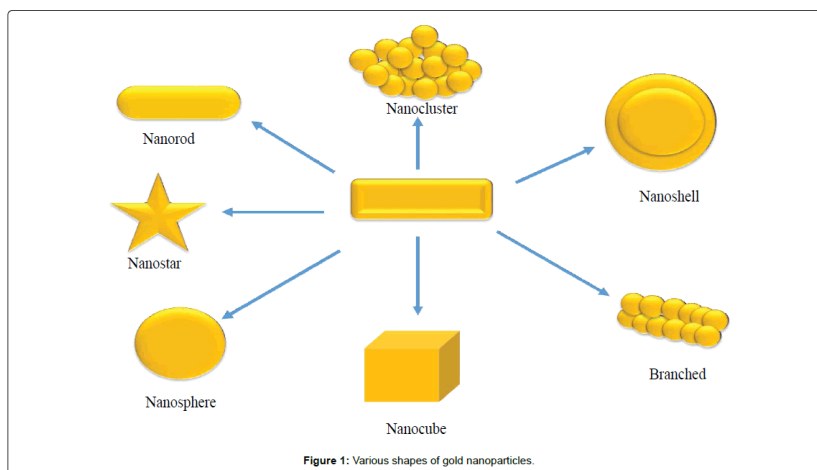


Fig. 3. Shapes of gold nanoparticles (Figure adapted from Alaqad & Saleh 2016)

MECHANISM OF TARGETED DELIVERY OF GOLD NANO PARTICLE

Targeted delivery of gold particle is achieved through two mechanisms, Passive Targeted through enhance permeability and retention effect and active targeting through receptor mediated endocytosis. Tumor vasculature is often abnormally leaky and lacks efficient lymphatic drainage, allowing nanoparticles, typically 20–200 nm in diameter and to preferentially accumulate in tumor tissues. In one study, delivery of AuNPs via mesenchymal stem cells (MSCs) increased tumor accumulation 2.4- to 9.3-fold compared to free AuNPs administered at the same dose, demonstrating significantly enhanced targeting via active carrier systems over passive EPR-based delivery (9).

Gold nanoparticles can be functionalized with targeting ligands such as peptides or antibodies, enabling them to bind to specific receptors on cancer cells. For instance, gold nanocarriers labeled with ^{125}I and conjugated with cyclic RGD peptides showed 150-fold greater binding affinity to $\alpha_v\beta_3$ integrin overexpressed in tumor cells as compared to unmodified controls, these probes also exhibited rapid and efficient tumor targeting within 10 minutes post-injection (10).

GOLD NANOPARTICLES IN DISEASE DETECTION

STRIP METHOD FOR EARLY DETECTION OF HEART ATTACKS

Heart attack is becoming common so for the early detection of heart attacks scientists are trying to find ways to make a more sensitive solution to test early detection of heart attacks. In heart attack victims the cardiac troponin marker is greatly expressed so the engineers at New York University School of Engineering and some engineers from Peking University have worked together and come up with a more sensitive test strip solution that helps in the early detection of heart attacks. They have used a common "cardiac troponin" cTn-I as a biomarker because of its high concentration or expression in victims of heart attack. If its high concentration gets detected in people then that person could be saved from getting heart attacks. This sensitive test strip basically helps to predict whether a person is going to have a heart attack or not (6).

The micro-plasma gold nanoparticles are mixed with antibodies against antigen cardiac troponin to make immuno-chromatographic test strips. The surface of the gold nanoparticles by "Microplasma-Assisted Synthesis of Colloidal Gold Nanoparticles" helps to attract more antibodies thus making the test more sensitive to detection. These gold particles are extremely sensitive and the detection depends on a chemical reaction that occurs between the antibodies on the strip and the antigen cardiac troponin expressed in people's blood (11)

GOLD NANOPARTICLES DELIVERING DRUGS IN CANCEROUS CELLS

Scientists are using gold nanoparticles loaded with drugs that are used to target the enzyme telomerase responsible for increasing telomere length in cancerous cells that results in unstoppable growth of cells. Usually in healthy cells the telomere cap gets shorten with time and cell cannot divide any further thus resulting in cell death and aging process starts but stem cells in tumor cells divide rapidly with long telomere lengths and quick repairing of telomeres. Such cells have shown unresponsiveness to treatments due to the enzyme activity (12).

The study done in lab on laboratory grown "melanoma skin cancer cells" used gold nanoparticles to deliver drugs to the heart of tumor cells as gold particles gets absorbed easily into the cells making the treatment and targeted drug delivery easy. The results showed that the drug reached its target shutting down the activity of the enzyme and stopping the growth of cancer cells (12).

GOLD NANOPARTICLES IN DISEASE DETECTION

Kidneys are the important organs of our body and important for survival because they filter wastes from blood and any problem in kidney could lead to serious problems. The old method for the early detection of kidney diseases used fluorescent organic dyes which were introduced into the target organs and then upon the exposure of invisible infrared light these dyes emitted radiations which were detected by

the detector. The use of these dyes does not produce good results because they accumulate in the skin and produce vague results and they clear out quickly from the target area so scientists had to inject fluorescent dyes many times. That's why scientists are now using gold nanoparticles that are of 6nm in size, inexpensive and stay for a long time and give sharper and clear images of the kidney. The other advantage is that they can easily be removed from the body during urination (13). Recent advances underscore the versatility of gold nanoparticles in both diagnostics and therapeutics. Luo et al., 2021 reviewed the development of gold nanoparticles (AuNPs) as contrast agents in cancer imaging, emphasizing their optical tunability and potential for enhanced diagnostic precision (14). A study demonstrated how gold nanorods enable photothermal therapy (PTT) and molecular detection for cancers such as breast, lung, and pancreatic cancer, due to their efficient light-to-heat conversion properties (15).

GOLD NANOPARTICLES ALONG WITH PEG AS EFFECTIVE AND IMPROVED ANTIBIOTIC DELIVERY MECHANISM

For the efficient target killing of bacteria gold nanoparticles were used in this study to improve the efficiency of drug delivery mechanism. In this study Polyethylene glycol, gold nanoparticles and Lincomycin, an antibiotic against *Staphylococcus aureus* and *Streptococcus pyogenes* were used (16). Gold nanoparticles were produced by a reduction reaction upon interaction of the aqueous extract of "Piper guineese" with "gold chloride" solution. These particles were then encapsulated with the drug and they called it as a Nano drug to treat many bacterial infections. This drug basically blocks the protein synthesis by blocking the peptide transfer step on the larger subunit of ribosome (50S) of bacteria (16).

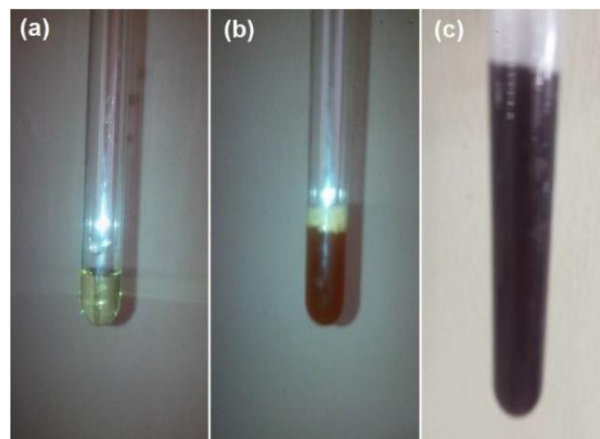


Fig. 4. (a) Shows chloride solution (b) shows aqueous piper extract and (c) is the biosynthesized gold particles formed by reduction reaction upon interaction of a and b solutions (Figure adapted from Shittu, 2017)

To check the functioning of the experiment 3 formulations were used and antibacterial assay was carried out. Bacterial petri plates were inoculated with these 3 formulations on different petri plates at 2 temperatures 40°C and 60°C to check which gives the best results (16), such as PND (PEG + gold nanoparticles + lincomycin), PN (PEG + gold nanoparticles), PD (PEG + drug).

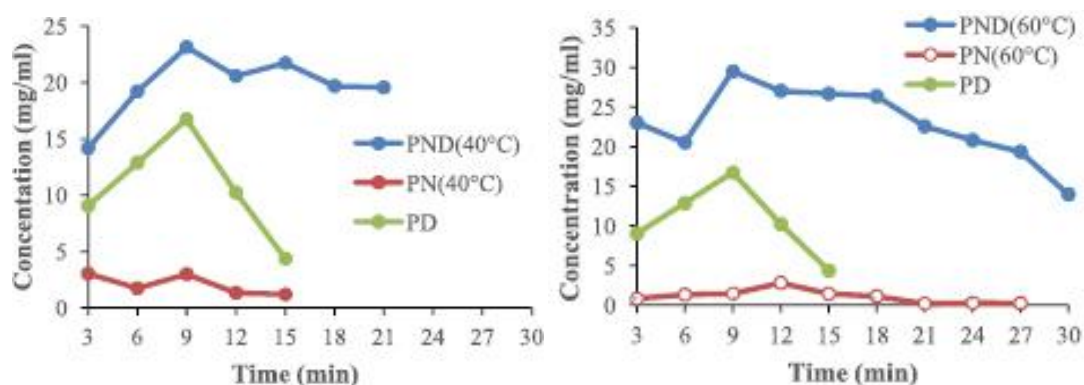


Fig. 5. Release capacity of drug at 40°C and 60°C. PND showing the highest drug release compared to the other two (Figure adapted from Shittu, 2017)

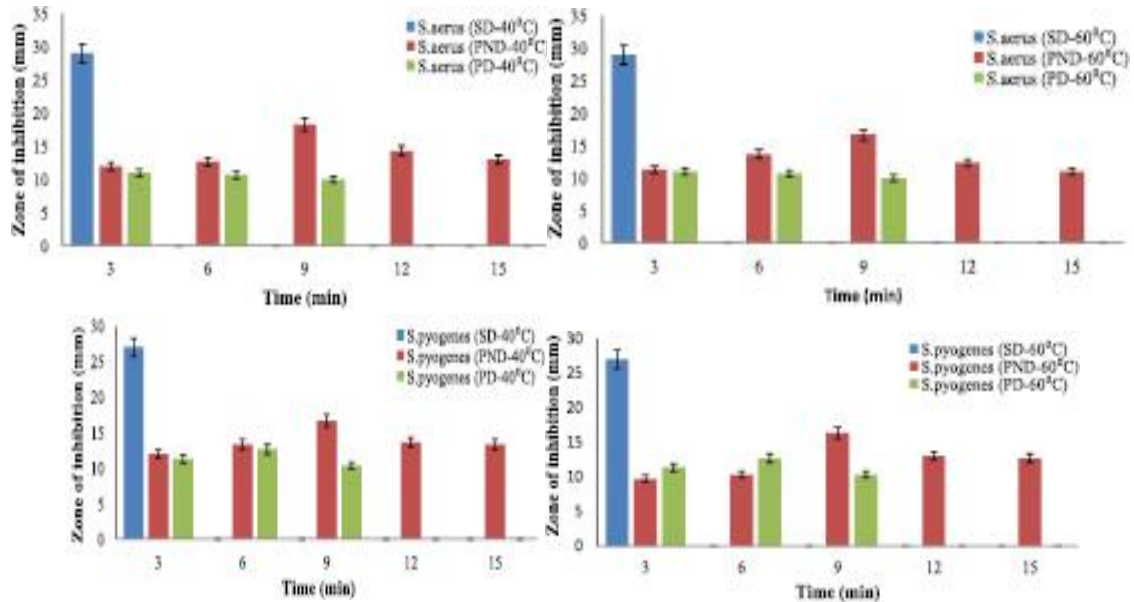


Fig. 6. Zone of inhibition: a and b showing the effect of 3 formulations at 40°C and 60°C for *S. Aureus* and the last two showing results for pyrogens at 40°C and 60°C (Figure adapted from Shittu, 2017)

The PND proved to show the quick release of drug in less time and more zone of inhibition compared to the others so that concluded PEG and Gold nanoparticles work best when applied together (16).

DESTRUCTION OF VIRUSES USING GOLD NANOPARTICLES

We are living in a world full of viruses and some of them are deadly to human beings. Vaccines are available against them but there is no such broad-spectrum vaccine which would show a complete cure or effectiveness against viruses. Viruses like Herpes, Dengue, Ebola, HIV, hepatitis etc. are those which are deadly to human beings. Sometimes doctors prescribe antibiotics and their overuse results in giving resistivity to the strains and they keep on mutating and a new strain arrives they are so smart that they somehow mutate themselves and escape. The making of vaccines against every viral strain is laborious and very expensive because out of many vaccines only 1 or 2 get selected and it takes years and years of trials and then years for a vaccine to get approved by FDA since safety issues are concerned. So, the scientists at “École polytechnique fédérale de Lausanne” (EPFL) University and Research Institute in Switzerland came up with a solution and a new way to destroy the deadly viruses using gold nanoparticles (17).

People at “Supramolecular Nano-Materials and Interfaces Laboratory” (SUNMIL) have made Gold Nanoparticles that mimics human cells or have receptors upon which virus binds to the human cells and try to trick or attract viruses towards them to infect them. So, when a virus comes near them the gold particles all together exert pressure on to that virus resulting in the breakage of a virus and a complete damage to it. Experiments performed on some strains of HSV, RSV, papilloma and dengue were successful and on animal level the mice infected with RSV got cured. This method could help us save many people from deadly viruses if this becomes successful in Human beings (17).



Fig. 7. Gold nanoparticles attack on virus (Figure adapted from Clara Marc 2017)

SUTURE FREE TECHNOLOGY FOR REPAIRING DAMAGED ORGANS

A promising suture free technique to repair damage organs is another wonderful blessing of gold nanorods. Since heart is the most vital organ in the body any damage in that area results in the improper functioning of the body. Injuries to the heart could lead to irregular heartbeats and sometimes in severe conditions it could lead to heart failure. Although tissue engineering or “cardiac patches” helps to save the heart from dying but sometimes the sutures may cause additional damage to the weakened or diseased heart. In order to minimize this problem, scientists developed a new safe suture free method to repair the damaged heart by the use of “gold nanorods” with “nanocomposite scaffolds of albumin electrospun”. The cardiac cells were added in the scaffolds containing gold nanorods and were placed in the muscular tissue of the heart. Then they were subjected to near infrared light of 808nm wavelength which was converted into thermal energy by the gold nanorods upon absorption. This change in energy resulted in the change in scaffold structure and helped the scaffold patch to attach to the heart walls to repair the damaged area. Soon this suture free way of repairing damaged organs would help to overcome the additional damages from suture technologies to the vital organs of the body (Fig. 6) (18).

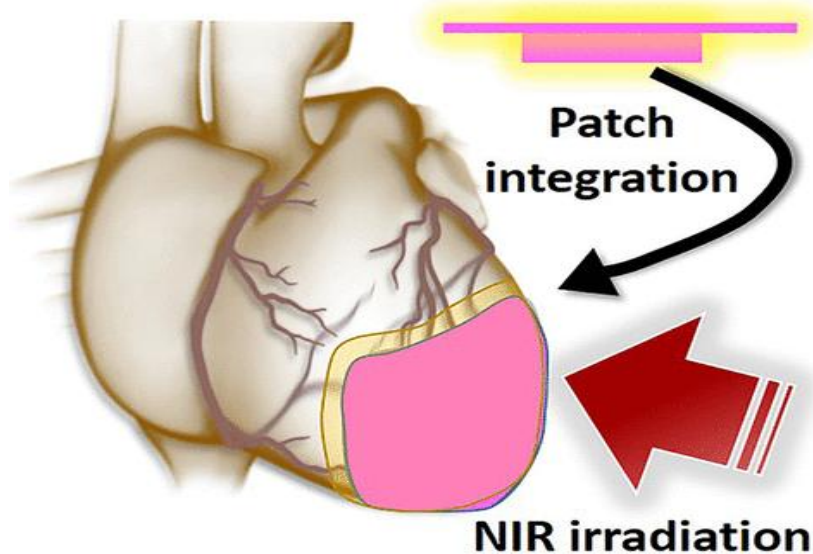


Fig. 8. Repairing damaged heart (Figure adapted from Malki et al., 2018)

COMPARATIVE ANALYSIS

Recent studies provide valuable quantitative insights into the relative toxicity and biodistribution of gold nanoparticles (AuNPs). For instance, in a comparative in vivo study using zebrafish, the lethal concentration causing 50% mortality (LC_{50}) was approximately 24.5 $\mu\text{g/L}$ for silver nanoparticles, compared to 41 mg/L for AuNPs, indicating significantly lower acute toxicity for gold nanoparticles under the same conditions (19).

In another chronic exposure study in mice, AuNPs administered intravenously at 2 mg/kg resulted in acute mortality and significant histopathological alterations across multiple organs. Lower doses (e.g., 1 mg/kg) induced only mild hematological effects, such as a 15–20% increase in lymphocyte counts, without overt organ damage (20).

CONCLUSION

This review highlights the several applications of gold nanoparticles in diagnostics, medicine, and biotechnology, where their unique optical, electronic, and structural properties have enabled sensitive, cost-effective, and rapid approaches for disease detection and therapy. Advances in AuNP-based platforms have shown significant potential in early diagnosis of cardiovascular disorders, renal dysfunction, and cancer, demonstrating their translational value in clinical practice. Further research is required to enhance the targeting specificity of gold nanoparticles for precise delivery, to optimize and scale up eco-friendly synthesis methods for sustainable production, and to develop strategies that minimize immune response

and cytotoxicity. Addressing these challenges will be essential for advancing AuNPs from experimental studies to safe and effective clinical applications.

CHALLENGES AND FUTURE DIRECTIONS

Despite their wide-ranging applications, gold nanoparticles face several challenges that limit their clinical translation. Potential cytotoxicity, particularly at higher concentrations or with long-term exposure, remains a major concern and requires detailed toxicological evaluation. Stability issues, including aggregation under physiological conditions, may affect reproducibility and therapeutic efficacy. Moreover, large-scale synthesis with consistent size, shape, and surface chemistry is difficult to achieve, posing challenges for regulatory approval. Addressing these limitations through surface modifications, biodegradable coatings, and standardized synthesis protocols could improve safety and translational potential.

Future directions for gold nanoparticles include their application in the targeted inactivation of highly pathogenic viruses. If viral eradication using gold nanoparticles prove successful in humans, it could provide a cost-effective therapeutic approach and facilitate the development of broad-spectrum antiviral agents, offering an advantage over conventional antibiotics and virus-specific drugs. Such broad-spectrum strategies hold the potential to address currently untreatable viral infections. However, the translation of these findings into clinical practice remains challenging, as issues related to nanotoxicity, large-scale biocompatible synthesis, immunogenicity, and regulatory approval must be systematically addressed before AuNP-based broad-spectrum antivirals can be clinically implemented.

Authors' contribution:

SU Conceptualization, write up; HAK, MZ & RF Data collection; SN, FH & ZH Critical analysis.

References:

- Alaqad K, Saleh TA. Gold and silver nanoparticles: synthesis methods, characterization routes and applications towards drugs. *Environ Anal Toxicol.* 2016;6(4):384.
- Roy A. Plant derived silver nanoparticles and their therapeutic applications. *Current Pharmaceutical Biotechnology.* 2021;22(14):1834-47.
- dos Santos Haupenthal DP, Mendes C, de Bem Silveira G, Zaccaron RP, Corrêa ME, Nesi RT, Pinho RA, da Silva Paula MM, Silveira PC. Effects of treatment with gold nanoparticles in a model of acute pulmonary inflammation induced by lipopolysaccharide. *Journal of Biomedical Materials Research Part A.* 2020;108(1):103-15.
- Baranes K, Shevach M, Shefi O, Dvir T. Gold nanoparticle-decorated scaffolds promote neuronal differentiation and maturation. *Nano letters.* 2016;16(5):2916-20.
- Wan D, Chen D, Li K, Qu Y, Sun K, Tao K, Dai K, Ai S. Gold nanoparticles as a potential cellular probe for tracking of stem cells in bone regeneration using dual-energy computed tomography. *ACS Applied Materials & Interfaces.* 2016;8(47):32241-9.
- Shagan A, [Institutional report]. New method uses light and gold nanoparticles for highly targeted, non-invasive drug delivery. Technion-Israel Institute of Technology. 2018.
- Hammami I, Alabdallah NM. Gold nanoparticles: Synthesis properties and applications. *J King Saud Univ Sci.* 2021;33(7):101560.
- Tiwari PM, Bawage SS, Singh SR. Gold nanoparticles and their applications in photomedicine, diagnosis and therapy. *Nanotechnol Rev.* 2015;4(3):249-66.
- Xu L, Xu M, Sun X, Feliu N, Feng L, Parak WJ, Liu S. Quantitative comparison of gold nanoparticle delivery via the enhanced permeation and retention (EPR) effect and mesenchymal stem cell (MSC)-based targeting. *ACS Nano.* 2023;17(3):2039-52.
- Hong L, Li W, Li Y, Yin S. Nanoparticle-based drug delivery systems targeting cancer cell surfaces. *RSC Adv.* 2023;13(31):21365-82.
- Becker KH, Zhu W. Gold nanoparticles show promise for early detection of heart attacks. New York University. 2015. Rowles D. Why gold nanoparticles offer a bright future for diagnostics and healthcare. 2018. [Online Report].
- Bavelaar B. Gold nanoparticles can deliver drugs into heart of cancer cells. Oxford University. 2016.

13. Zheng J. Gold nanoparticles may help improve understanding, detection of kidney disease. University of Texas at Dallas. 2016.
14. Luo D, Wang X, Burda C, Basilion JP. Recent development of gold nanoparticles as contrast agents for cancer diagnosis. *Cancers*. 2021;13(8):1825.
15. Kesharwani P, Ma R, Sang L, Fatima M, Sheikh A, Abourehab MA, Gupta N, Chen ZS, Zhou Y. Gold nanoparticles and gold nanorods in the landscape of cancer therapy. *Mol Cancer*. 2023;22(1):98.
16. Shittu KO, Bankole MT, Abdulkareem AS, Abubakre OK, Ubaka AU. Application of gold nanoparticles for improved drug efficiency. *Adv Nat Sci Nanosci Nanotechnol*. 2017;8(3):035014.
17. Marc C. Broad-spectrum non-toxic antiviral nanoparticles with a virucidal inhibition mechanism. *Nat Mater*. 2017;16(5):719-25.
18. Malki M, Fleischer S, Shapira A, Dvir T. Gold nanorod-based engineered cardiac patch for suture-free engraftment by near IR. *Nano Lett*. 2018;18(7):4064-73.
19. Ramachandran R, Krishnaraj C, Kumar VA, Harper SL, Kalaichelvan TP, Yun SI. In vivo toxicity evaluation of biologically synthesized silver nanoparticles and gold nanoparticles on adult zebrafish: a comparative study. *3 Biotech*. 2018;8(10):441.
20. Niżnik Ł, Noga M, Kobylarz D, Frydrych A, Krośniak A, Kapka-Skrzypczak L, Jurowski K. Gold nanoparticles (AuNPs)—toxicity, safety and green synthesis: a critical review. *Int J Mol Sci*. 2024;25(7):4057.

