Hailey Miller, a recent graduate of the University of Memphis with majors in Biomedical Engineering and Mathematics and minors in Biology and Chemistry, is deeply passionate about cancer research. Raised in Arlington, TN, her interest was sparked during her undergraduate years, leading her to pursue a career in cancer research at St. Jude Children's Research Hospital. Dr. Xiaohua Huang and Alberto Rodriguez played pivotal roles in her academic journey, providing invaluable mentorship and opportunities for research in Dr. Huang's lab. Hailey's achievements include being recognized as an undergraduate research scholar, undergraduate Honors with Thesis, and publishing twice as an author, notably for her work on nanoparticle breast cancer research. Looking forward, Hailey plans to pursue an M.D. and Ph.D. in Cancer Biology, specializing in Pediatric Oncology, to continue her work at St. Jude and advocate for childhood cancer research. Submitting her work to *QuaesitUM*, Hailey aims to inspire local students to pursue research careers. Her paper, "Analysis and Comparison of Hybrid Gold-Based Nanoparticles and Their Potential Use in Optical Spectroscopy and Cancer Nanomedicine," pushes boundaries in cancer treatment, offering a comprehensive perspective on the importance of nanomedicine in battling breast cancer and beyond.

Hailey Miller & Alberto Rodriguez

Analysis and Comparison of Hybrid Gold-Based Nanoparticles and Their Potential Use in Optical Spectroscopy and Cancer Nanomedicine

Faculty Sponsor
Dr. Xiaohua Huang

Abstract

Breast cancer, a global health concern, demands innovative solutions. Nanoparticles, with dimensions between 10-100 nm, present a promising avenue for breast cancer diagnosis and treatment. This study focuses on synthesizing and characterizing anisotropic nanoparticles, such as nano popcorns and nanostars, to optimize their potential in enhancing breast cancer detection sensitivity. Rigorous testing, including size measurement and stability assessment, aims to identify optimal nanoparticles for further development. Gold nanoparticles, particularly nanopopcorns and nanostars, exhibit distinct shapes with unique biomedical properties. Finite-Difference Time-Domain simulations aid in understanding their plasmonic properties, crucial for optimizing their performance. Despite promising results, challenges in clinical translation and the need for detailed safety and effectiveness studies underscore the complexity of implementing these nanoparticles in breast cancer therapeutics. Sustained multidisciplinary efforts and advancements in nanotechnology are essential for overcoming hurdles and realizing the transformative impact of nanoparticles in personalized breast cancer management.

Introduction

Breast cancer is a major public health issue worldwide, affecting millions of women worldwide, accounting for 25% of all cancer cases in women. In the United States alone, it is estimated that over 280,000 women will be diagnosed with breast cancer each year, with over 40,000 deaths [6]. Despite significant advances in breast cancer research, the high mortality rate associated with this disease remains a major challenge. One promising approach for breast cancer diagnosis and treatment involves the use of nanoparticles [5, 2, 11]. Nanoparticles are materials that have dimensions on a nanometer scale, typically between 10-100 nm. These particles have unique properties due to their small sizes, such as increased surface area and reactivity. Additionally, they can be engineered to have specific properties that make them ideal for biomedical applications [2, 7, 12]. They can be functionalized with ligands or antibodies that specifically target cancer cells, allowing for targeted delivery of therapeutic agents or contrast agents for imaging. In addition, nanoparticles can be engineered to have unique optical, magnetic, or thermal properties, making them ideal for various diagnostic and therapeutic applications [3, 1].

One of the key advantages of using nanoparticles in breast cancer diagnosis and treatment is their ability to enhance imaging techniques. Nanoparticles can be designed to serve as contrast agents for imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound. These contrast-enhanced imaging techniques offer improved sensitivity and specificity, allowing for the early detection and accurate localization of breast tumors. In the realm of breast cancer treatment, nanoparticles hold great promise for targeted drug delivery. Conventional cancer treatments, such as chemotherapy, often lack specificity, causing damage to healthy tissues along with cancerous ones. Nanoparticles can be tailored to selectively accumulate in tumor tissues, owing to their surface modifications with ligands or antibodies that recognize and bind to specific receptors overexpressed on cancer cells. This targeted drug delivery approach minimizes side effects and enhances the therapeutic efficacy of anticancer agents.

Moreover, the unique physical properties of nanoparticles open up avenues for innovative therapeutic strategies. Some nanoparticles exhibit hyperthermic effects when exposed to certain frequencies of light or magnetic fields, making them suitable for hyperthermia-based cancer treatment. This involves selectively heating the cancer cells, inducing apoptosis or cell death while sparing healthy surrounding tissue. The field of nanomedicine is also exploring the potential of nanoparticles in monitoring and predicting the response to treatment. By incorporating imaging probes or sensors into nanoparticles, clinicians can track the distribution of therapeutic agents in real-time and assess treatment efficacy. This personalized medicine approach allows for adjustments in treatment plans based on individual patient responses. Despite the considerable promise, challenges remain in the clinical translation of nanoparticle-based approaches. Issues such as biocompatibility, long-term safety, and scalability need to be addressed before widespread clinical adoption. Nevertheless, ongoing research and clinical trials are progressively advancing our understanding of nanoparticle applications in breast cancer, bringing us closer to more effective and targeted diagnostic and therapeutic strategies.

The various nanoparticles synthesized have unique optical and electronic properties that can be tuned by varying their size, shape, and composition. In this study, we focused on the synthesis and characterization of anisotropic nanoparticles—with irregular shapes, which often exhibit distinctive optical and electronic characteristics. Various testing was conducted to determine the synthesized particles' size, shape, and stability. The ultimate goal of this study is to optimize the usage of nanoparticles to increase detection sensitivity. By comparing and optimizing the properties of different nanoparticles, we can identify the most promising candidates for further development and functionalization. It is important to recognize that the size, shape, and composition of nanoparticles play pivotal roles in influencing their behavior and interactions with biological systems.

Our experimental approach involved a series of rigorous tests aimed at comprehensively understanding the key attributes of the synthesized anisotropic nanoparticles. Precise measurements were conducted to determine their size, ensuring accuracy in nanometer dimensions. Shape analysis was undertaken to determine the distinct geometries these nanoparticles adopted. Additionally, the stability of these nanoparticles under various conditions was thoroughly assessed, as stability is a critical factor influencing their performance in biological applications. The overarching objective of our study is to contribute to the optimization of nanoparticle utilization, specifically targeting enhanced detection sensitivity in the context of breast cancer diagnosis. Through systematic comparison and optimization of these properties, we aim to identify the most optimal nanoparticles for further development and functionalization.

By scrutinizing and fine-tuning the characteristics of anisotropic nanoparticles, we strive to unlock their full potential for biomedical applications, particularly in the early detection of breast cancer. The optimization process involves a meticulous examination of how variations in size and shape impact the nanoparticles' interaction with cancer cells. This nuanced understanding allows us to tailor these nanoparticles to exhibit optimal properties for increased detection sensitivity. Furthermore, the outcomes of our study hold the potential to pave the way for the development of advanced diagnostic tools and targeted therapies. Identifying and optimizing the properties of nanoparticles with superior detection capabilities will contribute significantly to the ongoing efforts to improve the precision and effectiveness of breast cancer diagnosis and treatment.

Gold nanoparticles exhibit distinct shapes, and two intriguing morphologies, namely nano popcorns and nano stars, have gained interest for their enhanced properties in biomedical applications. Nanospheres (NSP) and nanorods (NR) are two distinct forms of nanoparticles with unique characteristics that make them valuable in various scientific and technological applications [12]. Nanospheres are spherical nanoparticles with a uniform structure, and their properties can be precisely controlled by adjusting parameters such as size and composition. Due to their symmetry and predictable behaviors, nanospheres are often employed in drug delivery systems, imaging agents, and as components in sensor technologies. Their regular shape allows for consistent interactions with biological entities and controlled release of therapeutic agents. Nanorods are elongated nanoparticles with a rod-like structure, offering different optical and electronic properties compared to nanospheres [8, 9]. The aspect ratio, or the ratio of length to width, can be fine-tuned to achieve specific characteristics. Nanorods exhibit unique plasmonic properties, making them particularly useful in applications like Surface-Enhanced Raman Spectroscopy (SERS), where their shape enhances the electromagnetic field around them. This property is exploited in various sensing and imaging applications, as well as in the development of photothermal therapy for cancer treatment, where nanorods can efficiently convert light into heat to selectively destroy cancer cells.

Nanopopcorn (NPCs) possesses a unique structure resembling popcorn, with irregular shapes and high surface roughness. This irregularity in shape contributes to their distinctive optical properties, making them valuable for certain biomedical applications. The irregular surface morphology of NPCs enhances their surface area, providing more sites for functionalization and interaction with biological entities[8, 10, 11, 13] . This unique structure can be advantageous for targeted drug delivery, as well as for improving the sensitivity of diagnostic imaging techniques. On the other hand, nanostars (NSTs) exhibit sharp branches extending from a central core, providing an increased surface area compared to spherical nanoparticles. The enhanced surface area of nanostars is particularly beneficial for applications involving SERS and LSPR. These properties make nanostars attractive for use in biosensing, imaging, and therapeutic applications [7,8,10] .

Hollow nanoparticles, also known as nanocarriers or nanoshells, are a specialized class of nanoparticles characterized by their unique hollow interior structure. Unlike solid nanoparticles, hollow nanoparticles possess voids or cavities within their structures, creating a shell-like morphology. This hollowness can be advantageous in various applications, particularly in drug delivery and imaging. The central void provides an enclosed space that can be utilized to encapsulate therapeutic agents, such as drugs or imaging contrast agents. This encapsulation serves to protect the payload from degradation, enhance its stability, and control its release kinetics. The hollow structure also allows for the incorporation of multiple functionalities, such as targeting ligands or stimuli-responsive elements, further optimizing their performance for targeted drug delivery. Additionally, the hollow interior can serve as a reservoir for drugs and therapies, making these nanoparticles versatile tools in fields ranging from medicine to catalysis. The tunable properties of hollow nanoparticles, such as size, shape, and surface modifications, make them promising candidates for advancing nanotechnology applications with tailored and multifunctional capabilities [1, 2, 11] .

To gain a deeper understanding of the optical characteristics and behavior of gold nanopopcorns and nanostars at the nanoscale, researchers employ advanced computational techniques such as Finite-Difference Time-Domain (FDTD) simulations. Additionally, FDTD computational analysis allows us to model the interaction of light with complex nanostructures, providing valuable insights into their plasmonic properties. In the context of gold nanopopcorns and nanostars, FDTD simulations enable the investigation of their plasmonic properties, scattering and absorption spectra, and electromagnetic field enhancements that occur around these structures [4].

By leveraging FDTD simulations, researchers can predict and understand how these gold nanoparticles interact with light of different wavelengths. This knowledge is crucial for optimizing their performance in various biomedical applications, including imaging and therapy. FDTD simulations enable the fine-tuning of these nanoparticles' optical properties, allowing researchers to design particles with enhanced light-scattering characteristics or improved absorption in specific wavelength ranges. The distinctive shapes of gold nanoparticles offer unique advantages for biomedical applications. The combination of experimental characterization and computational modeling, especially through techniques like FDTD simulations, allows researchers to unravel the intricate optical properties of these nanostructures, paving the way for their tailored use in advanced diagnostics and therapeutic interventions.

Methods

Synthesis and Characterization of Gold Nanopopcorns and Nanostars

The nanoparticles were synthesized using established methods in literature. Briefly, a seed solution containing 1% of Chloroauric acid ($HAuCl_4$) was mixed with an aqueous solution of Sodium Citrate (38.8 mM), which served as the capping and stabilizing agent. Afterwards, 20mM of Sodium Borohydride ($NaBH_4$) was added to the solution dropwise and used as a strong reducing agent to reduce the gold precursor ($HAuCl_4$) from a 3+ charge to a 0, thus initiating a nucleation process between the gold atoms which in terms generate gold seeds with an average size of 5 nm. The solution turned from colorless to red indicating the formation of gold seeds.

After the seed solution preparation, a growth solution containing 200 µL of 10 mM HAuCl4 was prepared and mixed with 5mL of 0.1M CTAB (Hexadecyl trimethyl ammonium bromide), 30 µL of AgNO3 10mM was then injected into the solution and mixed for 5 minutes. It is known that $AgNO_3$ can act as a shape-directing agent by adsorbing onto specific crystal facets of the gold nanostructures during their growth. This preferential adsorption of silver ions on certain facets guides the anisotropic growth of gold, leading to the formation of popcorn with irregular shapes or nano stars with sharp branches. Afterwards, 100mM of ascorbic acid (AA) was used as a weak reducing agent substituting $NaBH_4$ in order to avoid over reduction of the gold precursor. By simply adjusting the ascorbic acid concentration, one can obtain a star (32 µL) or popcorn (90 µL) shape NP. Finally, 350 µL of the previously prepared seeds were injected into the growth solution, acting as catalyst for the creation of the anisotropic NPs (**Figure 2**).

UV-VIS spectrometer (Thermo Fisher, Madison, WI) was used to measure the absorbance spectra of the nanoparticles, which provided information on their plasmonic properties. The concentration and size of the particles was determined through nanoparticle tracking analysis (NTA) utilizing a NanoSight LM10 microscope (Malvern Instruments).

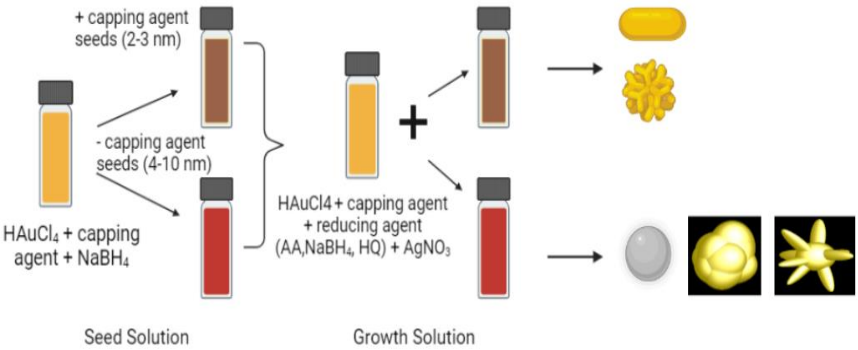


Figure 1. Overview of Turkevich seed mediated synthesis of anisotropic gold-based nanoparticles yielding different shapes based on the influence of the capping agent present and seed size.

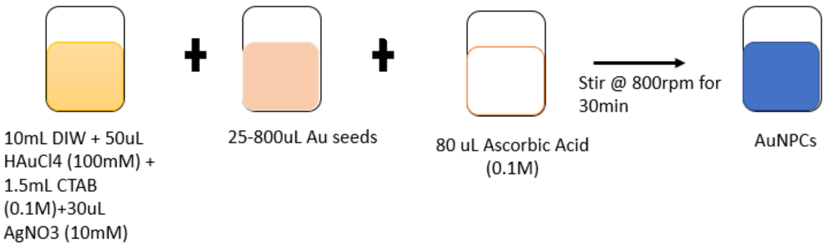


Figure 2. Synthesis of Au NanoPopcorns using the Turkevich seed mediated synthesis

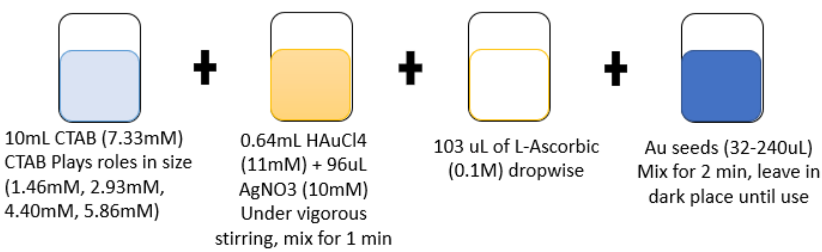


Figure 3. Synthesis of Au NanoStars using the Turkevich seed mediated synthesis.

Synthesis of Hollow Nanoparticles using Galvanic Replacement

In the synthesis of hollow nanoparticles using the galvanic replacement method, the following detailed steps were undertaken to achieve controlled and efficient formation of the desired hollow structures. First, a sacrificial template of silver nanoparticles was prepared through the reduction of a silver salt, typically silver nitrate, in the presence of a stabilizing agent, such as polyvinylpyrrolidone (PVP). The resulting silver nanoparticles were then washed thoroughly to remove excess reagents and unreacted species. Subsequently, a solution containing the precursor material for the desired shell, often gold chloride ($HauCL_4$), was prepared in a suitable solvent, such as water or ethanol. The concentration of the gold precursor in the solution was carefully optimized to ensure controlled deposition onto the silver nanoparticles during the galvanic replacement reaction. Typically, concentrations ranging from 1 mM to 10 mM were employed, with the specific concentration tailored to achieve the desired shell thickness and morphology.

The silver nanoparticles, acting as sacrificial templates, were immersed in the gold precursor solution under controlled reaction conditions. The galvanic replacement reaction between the silver core and gold precursor took place, leading to the gradual deposition of gold onto the surface of the silver nanoparticles. The silver core was concurrently dissolved into the solution. This process resulted in the creation of hollow gold nanoparticles, where the initial silver template was replaced by the deposited gold shell. To precisely control the reaction kinetics and achieve uniform hollow structures, the temperature and reaction time were rigorously optimized. Commonly, the reaction was carried out at elevated temperatures, often around 60-80°C, for a defined period, typically ranging from 1 to 4 hours. The reaction progress was monitored using techniques such as UV-Vis spectroscopy to observe the characteristic plasmon resonance shift associated with the formation of hollow structures.

After the completion of the galvanic replacement reaction, the hollow nanoparticles were separated from the reaction mixture through centrifugation and thoroughly washed to remove any residual reagents. The resulting hollow nanoparticles were characterized using various analytical techniques, including transmission electron microscopy (TEM) and dynamic light scattering (DLS), to confirm their morphology, size distribution, and structural integrity. By systematically adjusting the concentrations, reaction conditions, and parameters of the galvanic replacement process, this synthesis method enabled the controlled and reproducible fabrication of hollow nanoparticles with tailored properties. The optimized hollow nanoparticles hold significant promise for applications in catalysis, sensing, and biomedical fields.

Synthesis of Gold Core-Silver Shell Nanoparticles

The synthesis of the gold core-silver shell nanospheres involved a seed-mediated growth method, where gold nanospheres (Au NSP) were used as a seed to grow a silver shell around them. The silver shell was grown by adding a silver precursor (silver nitrate) (10 mM) to the 50nm gold nanospheres previously bought from BBI Solutions, along with a reducing agent (ascorbic acid) 100 mM and stabilizing agent (CTAC) 0.2M. The reaction was carried out under close containment of the growth solution due to the nature of the silver to oxidize when it interacts with oxygen. The growth process was initiated and allowed to proceed for 2 hours, during which the silver shell gradually formed around the gold core. This growth was visually monitored, and the distinctive change in color from red to orange indicated the successful deposition of the silver shell onto the gold nanospheres. The rapid alteration in color served as a real-time indicator of the nanomaterial synthesis.

The size of the nanoparticles could be controlled by varying the amount of silver precursor added to the reaction mixture, changing the size of the seeds or the number of seeds injected into the growth solution. This tunability is essential for tailoring the optical and physical properties of the nanospheres to meet specific requirements in applications such as catalysis, sensing, or imaging. Post-synthesis, the gold core-silver shell nanospheres were separated from the reaction mixture, typically through centrifugation, and thoroughly washed to remove any residual reagents. Characterization techniques such as UV-Vis spectroscopy and dynamic light scattering (DLS) were employed to assess the size distribution, morphology, and stability of the synthesized nanospheres.

Finite-Difference Time-Domain Modeling

The Ansys Lumerical software was used to conduct different Finite-Difference Time-Domain (FDTD) modeling of the near field of the Au NPCs and NSTs to observe the optical properties. Firstly, an FDTD domain was established with a conformal variant mesh with a size range of 0.25-3 nm generating 100 mesh on different regions of the FDTD model. Generating a large amount of mesh per region increases the accuracy of the test. This is due to the concept of the conformal mesh, which uses an integral solution of Maxwell’s equations near interfaces. Following the mesh refinement, a scattering cross-section test was introduced near the inner limit region of the FDTD. Additionally, a Frequency-domain Profile and Power monitor was introduced to visualize the electric field enhancement at different wavelengths ranging from 400 to 800 nm. We added a Total-Field Scattered-Field (TFSF) source, which measures scattering and absorbance in plasmonic materials. The TFSF source leads to a separation of the entire simulation region into two parts, the total field region containing both the incident and the scattered fields and the scattered field region containing only the scattered field. The frequency of the test was equivalent to 499 data points which ensures an accurate and clean plot. The electric field patterns in the near field of the nanostructures were evaluated using a Frequency-domain Profile and Power monitor. A perfectly matched layer (PML) was used to block any reflection of the scatter field from going back into the simulation area.

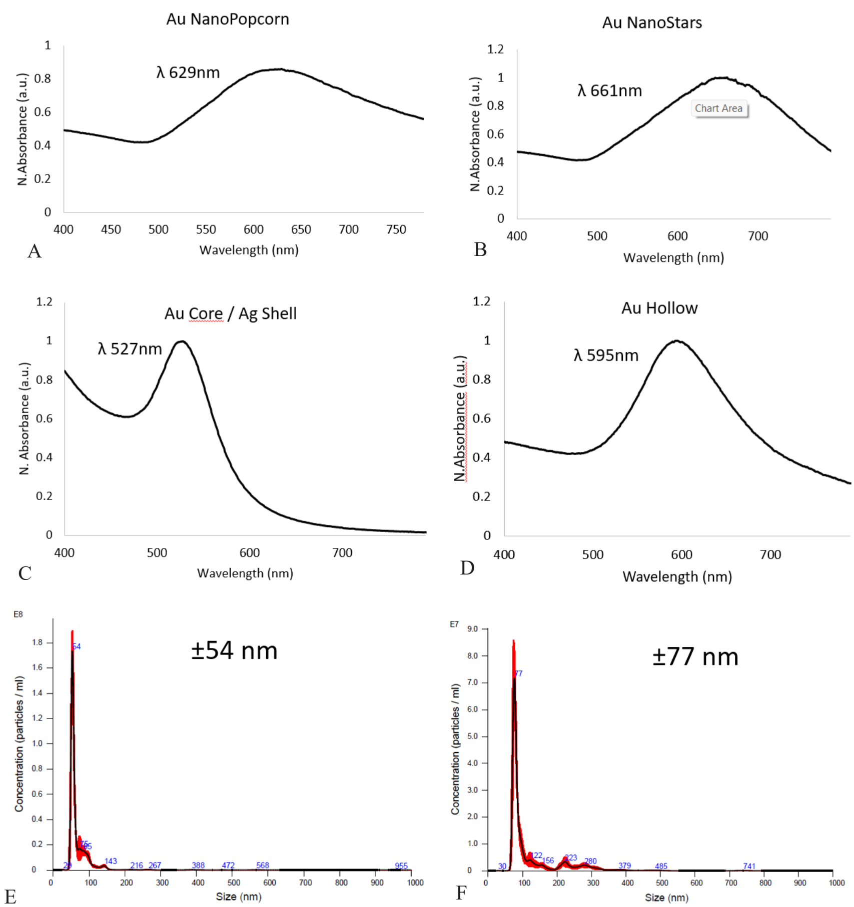
The simulations were conducted for a period of 1000 fs. All the simulations were performed with a background refractive index of 1.33. Lastly, an absorbance cross-section was inserted near the particle analyzed. The dielectric response of gold was taken from Johnson and Christy.[14] This rigorous simulation approach allows for a detailed exploration of the optical characteristics of gold nanoparticles.

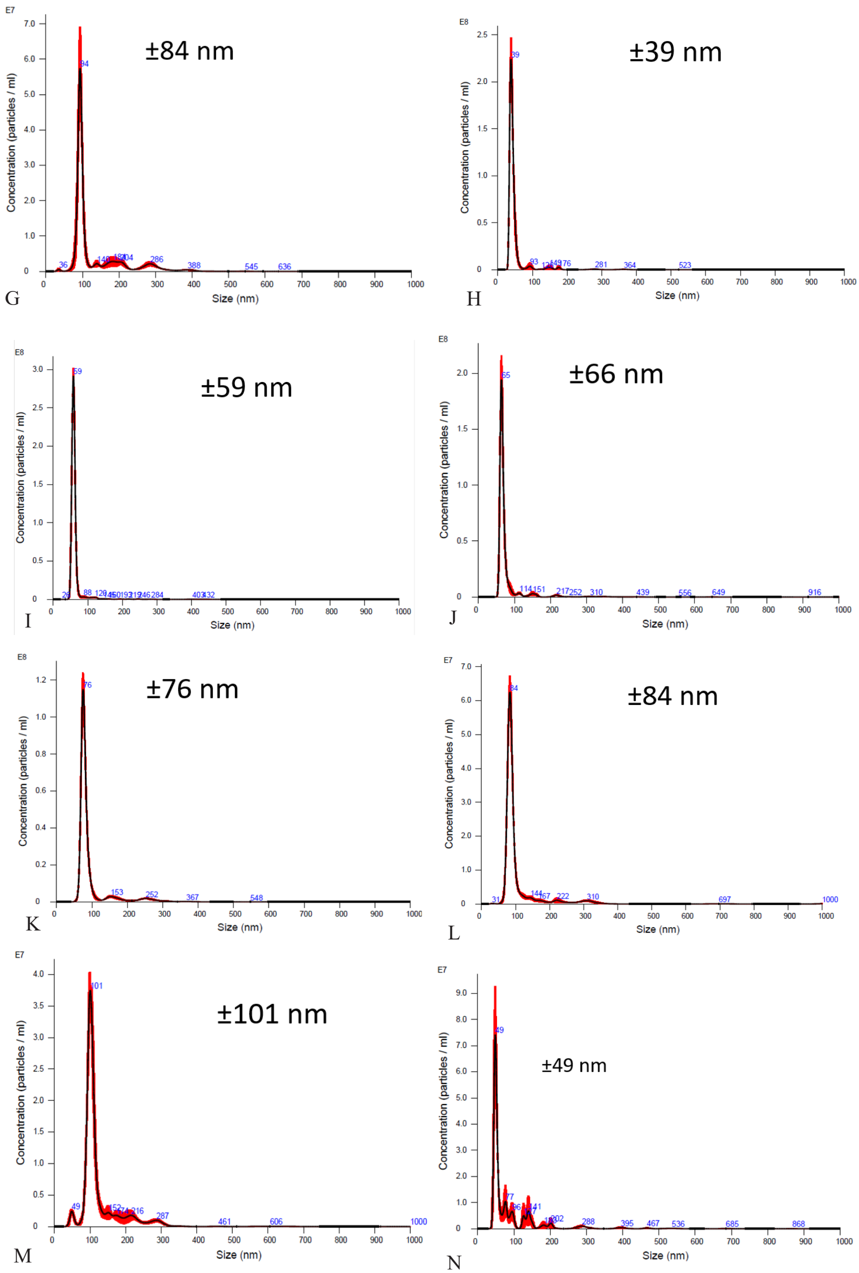
Results and Discussion

In the course of this study, we achieved the successful synthesis of a diverse array of nanoparticles, deliberately varying their shapes to explore the impact of morphology on their properties. The synthesized nanoparticles underwent a comprehensive characterization process utilizing a range of analytical techniques. UV-Vis spectroscopy provided valuable insights into the optical properties of the nanoparticles, offering information about their absorption and scattering behavior. NTA was employed to precisely determine the size distribution and concentration of the synthesized particles, contributing crucial information about their colloidal stability and uniformity.

Going beyond experimental measurements, FDTD modeling was employed to delve deeper into the electrodynamic behavior of the nanoparticles. This computational approach allowed for a meticulous analysis of the interaction between light and the nanoparticles, providing a detailed understanding of their plasmonic properties and how they respond to different wavelengths. The FDTD simulations were specifically conducted on a selected nanoparticle size, enabling a focused exploration of the size-dependent optical features and ensuring a nuanced comprehension of the nanoparticles' behavior at the nanoscale.

The integration of multiple characterization techniques offered a multi-faceted examination of the synthesized nanoparticles. This holistic approach not only validated the successful synthesis of nanoparticles with varied shapes but also enriched our understanding of their optical and dynamic characteristics. The synergy between experimental and computational analyses is instrumental in describing the intricate relationships between nanoparticle morphology and functionality, fostering advancements in fields such as nanomedicine, sensing, and catalysis.





G
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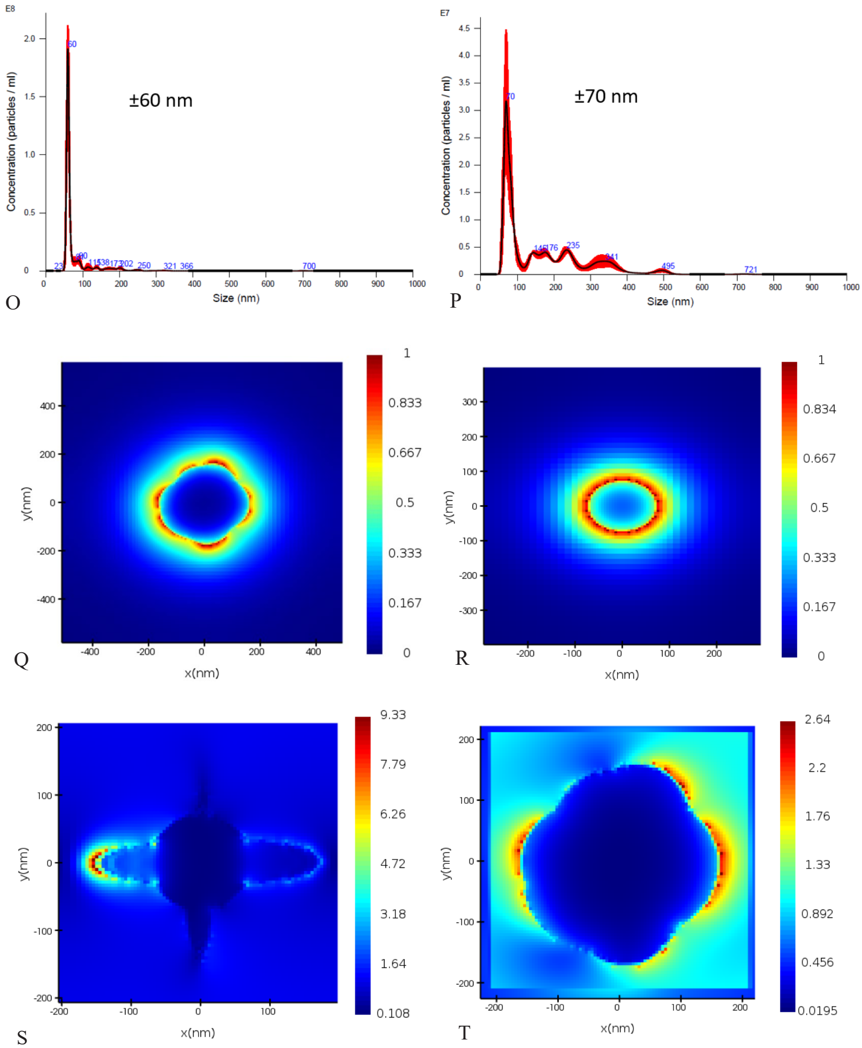

Figure 4. (**A-D**) UV-Vis showing the Localized Surface Plasmon Resonance (LSPR) of gold core-silver shell NPs (λ527 nm) and gold nanostars (λ661 nm), and gold nanopopcorns (λ629 nm), and gold hollow nanoparticles (λ595 nm). (**E-P**) NTA results with the average size of the of gold nano-stars (54 nm) found in **E/F/G**, gold nanopopcorns (59 nm) found in **H/I/J/K/L/M**, gold core-silver shell NPs (60 nm) found in **N/O**, and Au Hollow NPs found in **P**. (**Q-T**) FDTD modeling showing the electric field of the gold core-silver shell at (λ527 nm) and nanostar using at (λ661 nm), and the nanopopcorn at (λ529 nm) and (λ629 nm) using Total Field-Scattered Field (TFSF) source injected from the z-plane.

UV-Vis analysis of the synthesized nanoparticles revealed characteristic plasmonic peaks that corresponded to their different shapes and compositions. These plasmonic peaks arise from the collective oscillation for the free electrons in the metal nanoparticles in response to incident electromagnetic radiation. The plasmonic peaks can be used to determine the size, shape, and composition of the nanoparticles. For instance, we observed that the gold nano-popcorns showed a single broad LSPR peak around 629 nm which can either blue or red shift depending on the size, while the gold nano-stars showed a broad LSPR peak around 661 nm which follows the shifting based on the same features as spheres. On the other hand due to the plasmonic nature of the silver, and it being located on the surface of the system, as well as its spherical shape, the LSPR peak is located around 527nm (**Figure 4 A-D**).

NTA results showed that the synthesized nanoparticles had different size distributions, with some particles showing broad distributions and others showing narrow distributions. The gold nano-stars and nano-popcorns both showed a high degree of anisotropy and a narrow size distribution meaning high uniformity for both particles. The same results could be observed in the gold core-silver shell spherical nanoparticles. All particles showed an average size of 54-60 nm (**Figure 4 E-P**).

The Finite-Difference Time-Domain (FDTD) method is a rigorous and powerful tool for modeling nano-scale optical devices that solves Maxwell's equations in complex geometries. We used Anys-Lumerical software to model our anisotropic nanoparticles. FDTD simulation limits were first established followed by the creation of a 3-dimentioanl model of the particle to test. Afterwards, Total Field-Scattered Field (TFSF) source was selected as the recommended source for optical properties characterization based on the company suggestion. We also monitored the frequency-domain field and power to collect the field profile in the frequency domain from simulation results across some spatial region within the simulation in the FDTD. With this monitoring we were able to see the electric field behavior of the nano-popcorns, the bimetal nanoparticle and the nano-stars through a wavelength range from 400-800 nm. The Electric field map was handpicked based on the max LSPR peak location based on their UV-VIS (**Figure 4 Q-T**).

The plasmonic properties of gold nanoparticles are crucial for their applications in cancer nanomedicine. FDTD simulations reveal that both NPCs and NSTs exhibit strong localized surface plasmon resonances (LSPRs), which can be tuned by adjusting their size and shape. These resonances play a pivotal role in enhancing light-matter interactions, making these nanostructures ideal candidates for various biomedical applications. Gold nano popcorn and nano stars exhibited enhanced light absorption and scattering compared to spherical nanoparticles. FDTD simulations elucidate the specific wavelengths at which these nanostructures absorb and scatter light most efficiently. This knowledge is crucial for designing targeted therapies, such as photothermal therapy (PTT), where the absorbed light energy is converted into heat, selectively destroying cancer cells.

On the other hand, gold core-silver shell nanoparticles combine the advantageous properties of both gold and silver. The gold core contributes stability and biocompatibility, while the silver shell enhances the plasmonic and catalytic properties. FDTD simulations provide a detailed understanding of the optical response, plasmon resonances, and electromagnetic field enhancements of these hybrid nanostructures. The silver shell can be precisely tuned to manipulate the surface plasmon resonance, making these nanoparticles versatile in applications such as surface-enhanced Raman scattering (SERS) for sensitive cancer biomarker detection.

The FDTD computational analysis of these gold nanostructures provides critical insights into their behavior at the nanoscale, laying the foundation for their applications in cancer nanomedicine. The unique optical properties, plasmonic resonances, and enhanced light-matter interactions contribute to their potential roles in various aspects of cancer diagnosis and treatment. Their applications extend not only for diagnostics, imaging, and therapy, but it also has potential roles in targeted drug delivery, photoacoustic imaging, and synergistic multimodal treatments. The tunable plasmonic properties and enhanced light-matter interactions make these nanostructures versatile tools in the fight against cancer.

In this study, the synthesized NPs demonstrated a wide range of properties, which could be further explored for potential use in breast cancer research. The Au NSTs, with their high degree of anisotropy, have the potential to be utilized as imaging agents to improve the sensitivity and specificity of breast cancer detection. Au NSTs possess a unique surface plasmon resonance (SPR) which produces string localized electromagnetic fields that can enhance the contrast of imaging techniques such as photoacoustic imaging, X-ray computed tomography, and magnetic resonance imaging. By targeting these imaging agents to breast cancer cells, the nano-stars can provide a high level of sensitivity and specificity for cancer detection.

Moreover, the Au core-Ag shell-Au shell nanospheres (NSPs) exhibited a remarkable array of multifunctional properties, positioning them as an enticing option for targeted drug delivery to breast cancer cells. The inherent biocompatibility and stability conferred by the gold (Au) core establish a solid foundation for the overall nanoparticle structure. Simultaneously, the silver (Ag) shell introduces an additional layer of functionality, enhancing the therapeutic potential of the nanoparticles by acting as an antibacterial agent. The outer gold (Au) shell plays a pivotal role in providing a stable and functional surface for the targeted delivery of therapeutics to cancer cells. This outer layer not only contributes to the stability of the nanospheres but also serves as a versatile platform for the attachment of targeting ligands or other functional molecules. The synergistic combination of these three layers, each contributing distinct advantages, results in a nanosphere with multifunctional attributes.

The multifunctional nature of the Au core - Ag shell - Au shell nanospheres makes them a promising candidate for further in-depth investigation in the realm of targeted drug delivery. The potential to harness biocompatibility, stability, antibacterial properties, and targeted functionality in a single nanoparticle structure holds significant implications for advancing the precision and efficacy of therapeutic interventions in breast cancer treatment. Future research endeavors are warranted to explore and optimize the multifaceted capabilities of these nanospheres, paving the way for innovative strategies in personalized breast cancer therapeutics. The gold nanopopcorns showcased in this study exhibit substantial potential for advancing optical and detection sensitivity, primarily attributed to their unique and irregular surface morphology. The irregular surface structure of nanopopcorns, resembling popcorn, contributes to their distinctive op-tical properties. This irregularity enhances their surface area, providing more sites for functionalization and interaction with biological entities. The increased surface area of gold nanopopcorns not only holds promise for targeted drug delivery but also significantly augments their optical sensitivity, making them attractive candidates for applications in breast cancer research.

Furthermore, the nanopopcorns demonstrate superior conjugation efficiency compared to their counterparts, such as nanostars. The nanostar morphology, characterized by sharp branches extending from a central core, presents challenges in achieving efficient conjugation. The sharp peaks of nano-stars may limit the available sites for functionalization, potentially hindering the conjugation process. In contrast, the irregular and rough surface of gold nano-popcorns offers a more favorable environment for efficient conjugation, providing numerous opportunities for the attachment of functional molecules.

This advantageous feature of enhanced conjugation efficiency positions gold nano-popcorns as promising tools in the development of targeted therapies and diagnostic applications. Their potential to improve detection sensitivity, coupled with efficient conjugation capabilities, makes them valuable assets in the ongoing efforts to enhance precision and effectiveness in breast cancer diagnosis and treatment. Further research and exploration of these unique properties will likely unlock additional opportunities for the utilization of gold nano-popcorns in the realm of biomedical applications, paving the way for innovative advancements in personalized breast cancer therapeutics.

Conclusion

In the course of this study, we successfully synthesized a diverse array of nanoparticles, deliberately varying their shapes to explore the impact of morphology on their properties. Utilizing UV-Vis spectroscopy, NTA, and FDTD modeling, we comprehensively characterized the nanoparticles, gaining valuable insights into their optical and dynamic characteristics. The integration of multiple characterization techniques facilitated a multi-faceted examination of the synthesized nanoparticles, validating successful synthesis and enriching our understanding of their intricate relationships between morphology and functionality. The synergy between experimental and computational analyses is instrumental in advancing fields such as nanomedicine, sensing, and catalysis.

The plasmonic properties revealed by UV-Vis analysis, NTA results, and FDTD simulations demonstrate the potential applications of gold nanoparticles in cancer nanomedicine. From enhanced light absorption and scattering to tunable plasmonic resonances, these nanoparticles exhibit versatility for various biomedical applications. The unique properties of gold nano-stars make them promising imaging agents for breast cancer detection, while the multifunctional nature of gold core-silver shell-gold shell nanospheres positions them as attractive candidates for targeted drug delivery. Additionally, gold nano-popcorns show potential in increasing optical and detection sensitivity, providing better conjugation efficiency.

The synthesis and characterization of nanoparticles presented in this study demonstrate their potential for breast cancer research. The distinct physical and optical properties of each nanoparticle type provide opportunities for various applications such as imaging, sensing, and drug delivery. The nanoparticles' ability to target cancer cells specifically and their enhanced uptake in tumor tissue make them an attractive option for cancer diagnosis, targeted detection, prognosis, and therapy. However, the study also highlights the challenges associated with translating these nanoparticles to clinical applications. Despite the promising results, there is still a need for more detailed studies to optimize their interaction with cancer cells and to ensure their safety and effectiveness, which will be carried out in future semesters. Furthermore, ensuring the safety and effectiveness of these nanoparticles demands in-depth investigations, a task slated for exploration in upcoming research phases. Efforts to improve the reproducibility and scalability of the nanoparticle synthesis methods are also necessary to facilitate their translation to clinical use.

The findings presented here serve as a foundational stepping stone for future studies aiming to optimize the performance and safety profile of these nanoparticles in cancer research. The complexity of the challenges underscores the need for sustained research efforts, involving multidisciplinary collaboration and advancements in nanotechnology. As these nanoparticles continue to evolve, they hold the potential to reshape the landscape of breast cancer detection, diagnosis, and treatment. With a concerted focus on refining synthesis techniques, understanding cellular interactions, and addressing translational hurdles, nanoparticles emerge as promising candidates that could usher in a new era in personalized and targeted breast cancer therapeutics. The journey towards their clinical integration may be intricate, but the transformative impact on breast cancer management is a goal well worth pursuing through continued research and development.

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