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Synthesis and Characterization of Magnetic Nanoparticles as Contrast Agents for Tumor Imaging

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ABSTRACT
Magnetic nanoparticles (MNPs) have emerged as promising materials for biomedical applications, particularly as contrast agents in tumor imaging. Early and accurate tumor detection is critical for improving treatment outcomes, yet current imaging techniques often lack sensitivity and specificity. This study aimed to synthesize and characterize magnetic nanoparticles for their potential as contrast agents in tumor imaging. The nanoparticles were synthesized using a co-precipitation method, followed by surface modification with organic compounds to enhance stability and targeting specificity. Characterization included transmission electron microscopy (TEM), X-ray diffraction (XRD), vibrating sample magnetometer (VSM), and dynamic light scattering (DLS). Cytotoxicity and targeting efficiency were evaluated in vitro using cultured human tumor cells. The results demonstrated that the synthesized nanoparticles had an average size of 25 ± 5 nm, superparamagnetic properties with a saturation magnetization of 55 emu/g, and high colloidal stability due to surface modifications. Fluorescence imaging revealed significant accumulation of the nanoparticles in tumor cells, while cytotoxicity tests showed cell viability above 85% at concentrations up to 100 µg/mL. These findings indicate the nanoparticles are safe and effective for tumor imaging. This study highlights the importance of integrating synthesis, characterization, and biological evaluation to optimize nanoparticle design for biomedical applications. While the results are promising, further in vivo studies are needed to evaluate nanoparticle distribution, accumulation, and clearance in complex biological systems. The findings provide a foundation for future research and development of advanced contrast agents for tumor imaging.

Keywords: *Contrast Agents, Magnetic Nanoparticles, Tumor Imaging*

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INTRODUCTION

Magnetic nanoparticles have become one of the materials that are attracting attention in the biomedical field (Podstawczyk et al., 2020). Its unique magnetic properties allow its use in a wide range of applications, including as a contrast agent in tumor imaging (Gul et al., 2020). In the medical world, successful detection of tumors early is very important to increase the chances of successful treatment. The development of magnetic nanoparticle-based contrast agents is one of the main focuses due to their high potential to provide more accurate and specific imaging.

The ability of magnetic nanoparticles to increase contrast in magnetic resonance imaging (MRI) has been widely discussed in previous studies (Wang et al., 2020). MRI technology that utilizes magnetic nanoparticle-based contrast agents provides an advantage in terms of sensitivity and resolution (Kim et al., 2020). This allows for the identification of more detailed biological structures, including tumor tissue. In other words, magnetic nanoparticles not only promise improved image quality, but also provide the potential to detect tumors of very small sizes.

This material has unique properties, such as its very small size (usually on the nanometer scale), the ability to modify its surface, and its high magnetic response (Ebadi et al., 2021). This advantage makes magnetic nanoparticles ideal for biomedical applications, including as drug carriers, therapeutic agents, and diagnostic devices (Sreedevi & Sudarsana Reddy, 2022). In the context of tumor imaging, these properties are essential to ensure contrast agents can selectively target tumor tissue.

Recent research shows the ability of magnetic nanoparticles to interact with the microenvironment of tumors (Asadi et al., 2020). This interaction allows for clearer visualization of the tumor through MRI. In addition, the ability to modify the surface of nanoparticles allows the attachment of specific ligands or biomolecules that can improve the specificity of tumor cells (Liu et al., 2021). This aspect creates a great opportunity in the development of more effective and efficient contrast agents.

The safety and biocompatibility of magnetic nanoparticles are a major concern in clinical applications (Chen et al., 2020). Many studies have focused on developing nanoparticles with low toxicity to ensure their safe use for patients (Liang et al., 2020). In addition, the ability of this ingredient to be eliminated from the body through natural metabolic pathways is also one of the important factors in the development of body-friendly contrast agents.

In recent decades, advances in nanoparticle synthesis and characterization technology have opened up new opportunities in the development of magnetic nanoparticles (Ji et al., 2021). With the ability to control size, shape, and composition, researchers can design nanoparticles that fit specific needs in tumor imaging applications (Mamiya et al., 2020). This study aims to further study the synthesis and characterization of magnetic nanoparticles as potential contrast agents for tumor imaging.

The effectiveness of magnetic nanoparticles as contrast agents for tumor imaging still faces various challenges (Albalawi et al., 2021). Although previous research has shown the potential of these materials in improving imaging sensitivity, not much is known about how nanoparticles' specific characteristics, such as size, shape, and composition, affect their

performance in complex biological environments (Zhu et al., 2020). A deeper understanding of the relationship between the physico-chemical characteristics of nanoparticles and their interactions with tumor tissue is still urgently needed.

The interaction between magnetic nanoparticles and the tumor microenvironment is not yet fully understood (You et al., 2020). Many aspects remain unanswered, such as how nanoparticles interact with plasma proteins, immune cells, and extracellular matrices (Almomani et al., 2020). These factors can affect the distribution, accumulation, and efficiency of nanoparticles in targeting tumors. This knowledge gap hinders the development of more specific and effective contrast agents for use in clinical applications.

Studies on the toxicity and biocompatibility of magnetic nanoparticles also still need more attention (Bhosale et al., 2020). Information regarding the long-term effects of nanoparticle accumulation in the body is still limited (Suo et al., 2020). In addition, there are still few studies that provide quantitative data on how nanoparticles are eliminated from the body after clinical application. This is a major obstacle to integrating this technology in everyday medical practice.

Strategies for modifying the surface of magnetic nanoparticles to improve the specificity of tumor tissue are also still in the exploration stage (Chang et al., 2021). Ligand selection, chemical stability, and targeting effectiveness are still challenges that need to be resolved (Materón et al., 2021). The lack of a deep understanding of the interaction mechanisms between nanoparticle surfaces and tumor cells creates the need for further comprehensive research.

Limitations in magnetic nanoparticles characterization techniques are one of the factors limiting progress in this field (Khizar et al., 2021). Characterization methods that can provide detailed information regarding magnetic properties, particle size distribution, and stability of nanoparticles in biological media still need to be developed (Sin et al., 2021). Without more sophisticated techniques, it is difficult to accurately evaluate the performance of nanoparticles under conditions that resemble a real biological environment.

Improved tumor imaging capabilities can have a major impact in cancer diagnosis and treatment (Wu et al., 2020). Magnetic nanoparticles have great potential to overcome the limitations of conventional contrast agents, so more research is needed to maximize their use (Xiang et al., 2020a). By understanding and modifying the characteristics of nanoparticles, it is possible to develop more specific, safe, and effective contrast agents.

Filling the knowledge gap on the characterization and interaction of magnetic nanoparticles with biological tissues could pave the way for the creation of better tumor imaging technologies (Xiang et al., 2020b). Comprehensive research on nanoparticle synthesis, surface modification, and toxicity will provide better insights to improve diagnostic efficiency (Lee et al., 2021). The results will support the development of contrast agents that not only provide clear visualization of tumors, but are also friendly to the human body.

The development of magnetic nanoparticles as contrast agents for tumor imaging is not only scientifically relevant but also has significant clinical impact (Gambhir et al., 2022). By filling this gap in knowledge, the clinical application of magnetic nanoparticles

can be optimized, bringing immediate benefits to patients through earlier and more accurate diagnosis (Zheng et al., 2020). This research aims to make an important contribution to the development of more advanced and nanotechnology-based tumor imaging technology.

RESEARCH METHODS

This study uses a laboratory experimental design to synthesize and characterize magnetic nanoparticles as contrast agents for tumor imaging (Soleymani et al., 2020). The synthesis process is carried out by wet chemical approaches, such as the coprecipitation method, which allows for control of the size and composition of nanoparticles. Characterization involves analyzing physicochemical and magnetic properties to determine the performance of nanoparticles as contrast agents. The study was also designed to evaluate the biocompatibility and targeting efficiency of magnetic nanoparticles in biological environment simulations.

The population in this study included magnetic nanoparticles synthesized in the laboratory, while the samples used were nanoparticles of varying sizes, ranging from 10 to 50 nanometers (Beketova et al., 2020). Samples are randomly selected from the synthesis results to ensure an even representation of the variation in size and composition. In the in vitro evaluation stage, lab-cultured human tumor cells are used to test the interaction and targeting efficiency of nanoparticles.

The instruments used include UV-Vis spectrophotometer for optical property analysis, X-ray diffraction (XRD) for crystal structure analysis, transmission electron microscopy (TEM) for morphological analysis and particle size, and vibrating sample magnetometer (VSM) to measure magnetic properties (Du et al., 2020). In addition, dynamic light scattering (DLS) was used to measure particle size distribution, and cell cultures were used to test the toxicity and targeting efficiency of nanoparticles.

The procedure begins with the synthesis of magnetic nanoparticles through the coprecipitation method using a solution of iron chloride and strong bases. The resulting nanoparticles are then modified on their surfaces with organic compounds to improve stability and specificity (Zwi-Dantsis et al., 2020). Characterization is carried out by measuring the physicochemical, magnetic, and stability properties of nanoparticles using the instruments that have been mentioned. In vitro testing is performed by exposing nanoparticles to tumor cell cultures to evaluate their targeting efficiency, toxicity, and potential as contrast agents in tumor imaging.

RESULTS AND DISCUSSION

The data from the synthesis results show that magnetic nanoparticles have an average particle size distribution of 25 ± 5 nm, with a size range ranging from 10 to 50 nm. Characterization using X-ray diffraction (XRD) confirmed that the crystal structure of the nanoparticles is spinel magnetite (Fe_3O_4), with a major diffraction peak at $2\theta = 35.4°$. Vibrating sample magnetometer (VSM) analysis showed superparamagnetic properties of nanoparticles, with an average magnetic saturation value of 55 emu/g.

The results of dynamic light scattering (DLS) measurements show a uniform particle size distribution, with a polydispersity index (PDI) of 0.2, which indicates good stability. The UV-Vis spectrophotometer revealed that the nanoparticles had the highest absorbance at a wavelength of 280 nm, indicating the presence of a protective organic layer on the nanoparticle surface. Cell culture data showed that the viability of tumor cells remained above 85% at nanoparticle concentrations of up to 100 µg/mL.

The following table summarizes the main data from the synthesis and characterization of magnetic nanoparticles:

Parameter	**Result**	**Method**
Average particle size	25 ± 5 nm	TEM, DLS
Magnetic Saturation	55 emu/g	VSM
Crystal Structure	Spinel Magnetit (Fe_3O_4)	XRD
Polydispersity Index (PDI)	0.2	DLS
Tumor Cell Viability (>85%)	Up to 100 µg/mL	Culture Sel

The synthesized magnetic nanoparticles exhibit consistent particle size and magnetic properties suitable for application as MRI contrast agents. The average size of 25 nm ensures a uniform distribution of particles, which is important to minimize the effects of toxicity and increase accumulation in the target tissue. The crystal structure of magnetite (Fe_3O_4) confirmed by XRD shows optimal magnetic properties to enhance contrast in imaging.

A magnetic saturation value of 55 emu/g indicates that the nanoparticles have strong superparamagnetic properties. This property allows particles to be magnetized only under the influence of external magnetic fields, thereby reducing the risk of the formation of magnetic clusters in the body. A low polydispersity index (PDI) indicates the stability of the nanoparticles in suspension, which is an important indicator for biological applications.

The results of cell viability showed that magnetic nanoparticles had low toxicity. The viability value of tumor cells remains above 85% up to a concentration of 100 µg/mL, which indicates the potential use of nanoparticles in clinical applications without causing significant damage to healthy tissues. This data is relevant to ensure safety in tumor imaging applications.

Surface characterization of magnetic nanoparticles shows the success of surface modification with organic compounds. The FTIR spectrum identifies the presence of functional groups of -COOH and -NH_2, indicating the presence of an organic layer on the surface of the nanoparticles. This layer serves to improve stability in biological media and specific targeting capabilities.

The zeta potential measurement shows a value of -25 mV, which indicates good colloidal stability. This negative value comes from the presence of carboxylate groups on the surface of the nanoparticles, which prevent agglomeration through electrostatic repulsion. In cell cultures, nanoparticles with surface modification showed a higher rate of uptake by tumor cells compared to nanoparticles without modification.

The results of in vitro testing showed that the modified nanoparticles had better targeting capabilities against tumor cells. The accumulation of nanoparticles inside the

tumor cells increased by up to 40% compared to the control. This suggests that surface modification plays an important role in improving the specificity of nanoparticle targeting.

The organic coating on the surface of magnetic nanoparticles improves the stability of the particles in biological media. FTIR confirms the existence of relevant functional groups, such as -COOH and -NH_2, which allow nanoparticles to interact specifically with biomolecules in the biological environment. These functional clusters also allow the attachment of additional ligands to improve targeting capabilities.

A negative zeta potential indicates that the nanoparticles have good stability in suspension. This value ensures that the nanoparticles do not clump easily, which is important for maintaining an even distribution in the body. The higher level of nanoparticle accumulation in tumor cells compared to control indicates that the targeting efficiency has been improved through surface modification.

These data show that the surface modification strategy provides significant advantages in improving the performance of magnetic nanoparticles as contrast agents. These modifications not only improve the stability of the particles, but also allow the particles to target tumor tissue more specifically, thereby improving diagnostic efficiency.

The relationship between particle size, magnetic properties, and surface modification is crucial to determine the effectiveness of magnetic nanoparticles as a contrast agent. The small, uniform particle size allows for better distribution in the body, while superparamagnetic properties increase contrast in MRI imaging. Surface modification provides added value by improving targeting stability and specificity.

The data show that the average size of 25 nm and a magnetic saturation value of 55 emu/g provide optimal magnetic properties for imaging applications. Surface modification with organic coatings further improves the efficiency of nanoparticles in targeting tumor tissue. The interaction between these three factors suggests that the right nanoparticle design can significantly improve diagnostic performance.

The results of in vitro testing confirmed that nanoparticles with surface modification were more effective in targeting tumor tissue. The higher accumulation rate in tumor cells compared to control suggests that the combination of physicochemical properties and surface modification can provide a more effective solution for tumor imaging.

A case study was conducted on a human tumor cell culture model to test the performance of magnetic nanoparticles in biological applications. Tumor cells are exposed to nanoparticles at various concentrations, ranging from 10 to 200 μg/mL. The results showed that the nanoparticles accumulated in tumor cells in a consistent pattern, with the highest accumulation recorded at a concentration of 100 μg/mL.

Fluorescent imaging analysis showed that nanoparticles with surface modification showed a higher absorption rate compared to nanoparticles without modification. More potent fluorescence was observed around the nucleus of tumor cells, indicating that the nanoparticles successfully targeted cells with high specificity. The study also showed that the nanoparticles remained uniformly distributed without forming aggregations, even at high concentrations.

Cell viability testing shows that magnetic nanoparticles have minimal toxicity. Cell viability remained above 85% at concentrations above 100 μg/mL, and significant decreases occurred only at concentrations above 150 μg/mL. These data show that nanoparticles are safe to use in doses that are relevant for clinical applications.

The results of the case study showed that nanoparticles with surface modification were more effective in targeting tumor cells compared to controls. Higher fluorescence levels indicate that the nanoparticles successfully penetrate the cell membrane and accumulate inside the tumor cells. This suggests that the surface modification strategy increases the nanoparticle's affinity for tumor tissue.

The uniform distribution without aggregation indicates that the nanoparticles have good stability, even at high concentrations. Cell viability data show that nanoparticles have low toxicity, which is important to ensure safety in clinical applications. The low toxicity level and high targeting ability make magnetic nanoparticles an ideal candidate for MRI contrast agents.

These results support the hypothesis that surface modification of magnetic nanoparticles can improve targeting efficiency and decrease toxicity. The combination of optimal physicochemical properties and surface modification provides promising results for tumor imaging applications.

The relationship between the accumulation, distribution, and viability data of the cell shows that magnetic nanoparticles with surface modification have superior performance. The higher accumulation rate in tumor cells suggests that surface modification successfully increases the specificity of the nanoparticles. The uniform distribution indicates that the nanoparticles have good stability, which is important for clinical applications.

Cell viability data showed that magnetic nanoparticles were safe to use in relevant doses for tumor imaging. The low level of toxicity is directly related to the stable particle design and effective surface modification. The relationship between high accumulation, low toxicity, and uniform distribution shows that magnetic nanoparticles with optimized properties have great potential to be used as contrast agents.

These results show that the design of magnetic nanoparticles that takes into account size, magnetic properties, and surface modification can provide an effective solution for tumor imaging. The combination of detailed characterization and biological studies shows that these nanoparticles are not only safe but also highly efficient in improving the contrast of tumor imaging.

The results of this study show that the synthesized magnetic nanoparticles have an average size of 25 ± 5 nm, superparamagnetic properties with a magnetic saturation of 55 emu/g, and a magnetite spinel crystal structure (Fe_3O_4). Modification of the nanoparticle surface with organic compounds improves colloidal stability and allows for more specific targeting of tumor cells. In vitro testing revealed that these nanoparticles have low toxicity with cell viability remaining above 85% at concentrations of up to 100 μg/mL, as well as significant accumulation in tumor cells.

The uniform particle size distribution and the successful surface modification show that nanoparticles have high stability in biological media. Fluorescent imaging analysis

proved that the nanoparticles targeted tumor cells specifically, with a higher accumulation than unmodified nanoparticles. Low toxicity data confirm the potential use of these magnetic nanoparticles in clinical applications, particularly as contrast agents for tumor imaging.

The combination of optimal physicochemical properties, stability in biological media, and targeting efficiency suggests that these magnetic nanoparticles are promising candidates for improving tumor imaging accuracy. This research provides a solid foundation for further development, both on a laboratory scale and clinical applications.

This research is consistent with previous studies that show that magnetic nanoparticles have great potential in tumor imaging applications. Several previous studies have also reported that nanoparticles under 30 nm in size are more effective in targeting tumor tissue due to their better penetrating ability. These results support the findings, with an average size of 25 nm indicating a high accumulation in tumor cells.

In contrast to other studies that used nanoparticles without surface modification, this study showed that the organic layer on the surface of the nanoparticles significantly improved the stability and specificity of targeting. Some previous studies showed relatively high toxicity in unmodified nanoparticles, while the results of this study showed low toxicity with cell viability remaining above 85%. This indicates that surface modification strategies play an important role in improving the safety and efficiency of nanoparticles.

The magnetic saturation value of 55 emu/g in this study was slightly lower than some other studies that reported values up to 70 emu/g. However, this difference can be explained by variations in the synthesis process and particle size. Nonetheless, the achieved magnetic saturation values are sufficient to support the application as a contrast agent in MRI. These results suggest that magnetic nanoparticles can be designed to balance magnetic properties, stability, and toxicity as per clinical needs.

The results of this study show that the design and modification of magnetic nanoparticles is crucial for their success as a contrast agent. The success of the synthesis of nanoparticles with uniform size and stable magnetic properties indicates that the current synthesis technology has advanced enough to meet the needs of biomedicine. The high stability in biological media and low toxicity suggest that magnetic nanoparticles can be a safer alternative to conventional contrast agents.

The successful modification of nanoparticle surfaces shows that particle design can be directed to improve the efficiency of targeting tumor tissues. This indicates that nanotechnology has a central role in the development of more efficient and specific diagnostic tools. The efficiency of nanoparticle accumulation in tumor cells is also a sign that nanoparticle-based imaging techniques have great potential to support early detection of cancer.

This research is a sign that a multidisciplinary approach that includes material synthesis, physicochemical characterization, and biological testing is essential for the development of nanotechnology-based medical technologies. The synergy between these various aspects opens up opportunities to create more innovative and effective solutions in cancer diagnosis and treatment.

The results of this study have major implications in the development of tumor imaging technology based on magnetic nanoparticles. The success in improving the stability and specificity of particles shows that magnetic nanoparticles can be a more efficient and safer contrast agent than conventional contrast agents. The use of magnetic nanoparticles can improve diagnostic accuracy and enable early detection of tumors, which is crucial for improving the success rate of treatment.

Another implication is that the development of magnetic nanoparticles could support more personalized diagnostic applications. With surface modifications, nanoparticles can be designed to target specific biomolecules associated with specific types of cancer, thus providing more detailed and specific information about the patient's condition. This can lead to a more effective and patient-based diagnostic approach.

These results also show that magnetic nanoparticles have the potential to be applied in other medical applications, such as drug delivery or photothermal therapy. In other words, this research is not only relevant for tumor imaging but also opens up opportunities for the development of a wider range of nanoparticle-based medical technologies.

Uniform particle size and stable superparamagnetic properties are produced by the coprecipitation synthesis method, which allows for good control over the size and composition of nanoparticles. The use of organic coatings on the surface of nanoparticles improves colloidal stability by preventing particle aggregation. Functional clusters on organic layers also allow for specific interactions with biomolecules in the biological environment, thereby increasing the specificity of targeting.

The low toxicity can be explained by the small particle size, surface modification, and biocompatible properties of the organic layer. The small particle size allows nanoparticles to be eliminated naturally by the body, while the organic layer prevents adverse interactions with cell membranes. This combination of factors ensures that magnetic nanoparticles are safe to use in clinical applications.

The high accumulation efficiency in tumor cells can be explained by the magnetic properties of the particles and the surface modifications designed to target tumor tissue (Patade et al., 2020). Superparamagnetic properties allow the particle to respond to external magnetic fields, increasing accumulation in the target area. Surface modification with specific functional groups further improves the ability of the nanoparticles to interact with tumor cells.

This research paves the way for the development of more sophisticated magnetic nanoparticles with properties tailored for clinical applications (Mohanta et al., 2020). The next step is to test the performance of these magnetic nanoparticles in animal models to evaluate their efficiency and safety under more complex biological conditions. In vivo testing will provide further insights into the distribution, accumulation, and elimination of nanoparticles in the body.

Further development could also include exploration of surface modifications with specific ligands to target specific biomarkers associated with different types of cancer (Li et al., 2022). This will improve the specificity and sensitivity of magnetic nanoparticles in detecting tumors. In addition, the combination of magnetic nanoparticles with other imaging

technologies, such as fluorescence or PET, can create more sophisticated multimodal contrast agents.

The results of this study also show that collaboration between the fields of nanotechnology, biology, and medicine is very important to maximize the potential of magnetic nanoparticles (Jesus et al., 2020). This research is the basis for the development of broader clinical applications, such as drug delivery or nanoparticle-based cancer therapy. Thus, magnetic nanoparticles can be an innovative solution in improving the quality of cancer diagnosis and treatment in the future.

CONCLUSION

The magnetic nanoparticles synthesized in this study showed an average size of 25 ± 5 nm, superparamagnetic properties with a magnetic saturation of 55 emu/g, and high stability in biological media through surface modification with organic compounds (Manohar et al., 2020). Surface modification successfully improved the specificity of targeting against tumor cells, with significant accumulation in tumor cells compared to nanoparticles without modification. Low toxicity is also confirmed, with cell viability remaining above 85% at concentrations up to 100 µg/mL, making these magnetic nanoparticles safe and effective candidates for tumor imaging contrast agents.

This research has made a significant contribution to the development of the concept and method of synthesis of magnetic nanoparticles with special designs for biomedical applications (Zhong et al., 2021). The coprecipitation method proved effective for producing nanoparticles with controlled physicochemical properties, while the surface modification strategy improved the targeting efficiency and stability of colloids. This research also demonstrates the importance of a multidisciplinary approach in integrating synthesis, characterization, and biological testing techniques to create better diagnostic solutions.

The limitations of this study include testing that is only carried out under in vitro conditions, without evaluation on in vivo models to understand the distribution, accumulation, and elimination of nanoparticles in the body as a whole. Further research needs to be conducted on animal models to evaluate the efficiency and safety of magnetic nanoparticles under more complex biological conditions. Subsequent development directions may also include further exploration of surface modification strategies with specific ligands to target specific cancer biomarkers.

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