

Photothermal and magnetic studies of Ni@Au nanotubes for anti-cancer therapies

Anton Anikin¹, Alena Shumskaya², Anna Motorzhina¹, Anastasia Gurevich³,
Sergey Bedin⁴, Ilia Doludenko⁴, Dinara Khairtadinova³, Victor Belyaev¹, Kateryna Levada¹,
Valeria Rodionova¹, Larissa Panina³

¹ Immanuel Kant Baltic Federal University, 14A Nevskogo Str., Kaliningrad 236016, Russian Federation

² Institute of Chemistry of New Materials of the National Academy of Sciences of Belarus, 36 F. Skorina Str., Minsk 220141, Republic of Belarus

³ National University of Science and Technology "MISIS", 4-1 Leninsky Ave., Moscow 119049, Russian Federation

⁴ A.V. Shubnikov Institute of Crystallography, Kurchatov Complex of Crystallography and Photonics, National Research Centre "Kurchatov Institute", 59 Leninskiy Ave., Moscow 119333, Russian Federation

Corresponding author: Anton Anikin (anikinanton93@gmail.com)

Received 1 December 2024 ♦ Accepted 10 February 2025 ♦ Published 30 June 2025

Citation: Anikin A, Shumskaya A, Motorzhina A, Gurevich A, Bedin S, Doludenko I, Khairtadinova D, Belyaev V, Levada K, Rodionova V, Panina L (2025) Photothermal and magnetic studies of Ni@Au nanotubes for anti-cancer therapies. *Modern Electronic Materials* 11(2): 81–91. <https://doi.org/10.3897/j.moem.11.2.143172>

Abstract

Anisotropic ferromagnetic micro- and nanoparticles made of 3d metals demonstrate the ability to effectively influence micro- and nanoscale biological entities through hyperthermia and mechanical vibrations induced by magnetic fields. Multifunctional nanoparticles designed for combined therapies are particularly effective. This study explores the potential application of Ni@Au nanotubes to synergize magnetomechanical effects with photothermal heating. The orientation of nanotubes in a magnetic field was demonstrated by changes in the intensity of the light beam passing through a water suspension of nanotubes. The gold coating doubled the optical absorption of the solution in comparison with pure nickel nanotubes and resulted in the appearance of a resonance-enhanced peak in the range of 700–800 nm, the position of which is in accordance with theoretical calculations. The photothermal performance of nanotube solutions was quantitatively assessed by determining the photothermal conversion coefficient, which increased due to gold coating. However, it's worth noting that the gold coating did not significantly reduce nanotube cytotoxicity in hepatocyte-derived cellular carcinoma cells (Huh7). The potential reasons for this outcome include the large particle size and non-uniform gold coating. Nevertheless, the combination of two anti-cancer therapies employing the same type of particles offers the opportunity to reduce particle concentration while maintaining the required therapeutic efficacy.

Keywords

ferromagnetic nanotubes, nanoparticles, template synthesis, photothermal conversion, magneto-mechanical stimulation, biomedicine

1. Introduction

While significant progress has been made in cancer treatment, the substantial side effects associated with many

therapeutic methods have driven the investigations to the development of localized treatment approaches. Specifically, research has shown that magnetic nanoparticles, studied extensively for hyperthermia over several decades [1–5], hold significant potential for inducing

apoptosis in cancer cells through mechanical vibrations activated remotely by a low-frequency magnetic field, typically in the range of several tens of hertz [6–9]. These magnetic particles transmit the energy of their mechanical vibrations to micro- and nanoscale biological structures within an extremely confined area. The particle size and shape play a key role in delivering mechanical energy to cells. Ferromagnetic particles with lateral dimensions of 100 nm to a few micrometers made of 3d metals in the form of disks, wires and tubes [8, 10–16] have been proposed for such manipulations. Furthermore, ferromagnetic particles made of iron group metals, due to their higher magnetic susceptibility compared to iron oxide particles, can exert a more significant impact with the same quantity.

Ferromagnetic nanowires and nanotubes have a strong shape anisotropy which tends to maintain their magnetic moment in parallel to the axis. This helps to transfer the mechanical torque provided by the external rotating or oscillating magnetic field to biological objects. They are produced by electrodeposition in ion-track membranes [17, 18]. Pore sizes (20–500 nm) and their density are determined by the irradiation parameters of the membranes and the subsequent etching process, providing control over the diameter and length of such particles. In comparison to nanowires, nanotubes (NTs) offer specific potential advantages. The deposition modes enable the creation of NTs with the desired wall thickness but larger scattering cross-section, which makes it possible optical investigation of their dynamics in external magnetic fields. Lower density enables them to float in fluids (including biological ones), whereas metallic nanowires tend to agglomerate more actively and, consequently, precipitate faster.

On the other hand, multifunctional particles with applications spanning cancer therapy and bio-analytical systems are actively being developed [19–21]. For example, magnetomechanical intervention can be combined with local photothermal heating effects. Ferromagnetic nanostructures with a gold coating typically exhibit higher optical absorption compared to similar structures without coating. This suggests a higher degree of photothermal heating of such nanostructures [22–24]. In terms of bioapplications, a gold coating can enhance biocompatibility, enable further chemical functionalization and labeling with fluorescent tags, and reduce agglomeration effects.

This study investigates the magnetic, optical, and photothermal properties of nickel nanotubes with gold coating (Ni@Au NTs). The magnetic-plasmonic NTs were recently proposed to form efficient SERS substrates (Surface Enhanced Raman Scattering) to detect trace quantities of explosive or other materials with complex molecules [25], owing to plasmon resonance. In this case, magnetic properties of particles were used for controlling their distribution to achieve optimal amplification of the Raman signal by several orders of magnitude, and to obtain a finer spectrum structure. In our case, photothermal

properties were investigated at the wavelength of the radiation source in the near-infrared range within the plasmon resonance band, corresponding to the first biological transparency window, spanning between 700 and 950 nm [26]. The rotations of nanotubes by external magnetic field were assessed thanks to a large scattering cross-section of Ni@Au NTs, which depends on their orientation with respect to the irradiation wavevector. To assess the cytotoxic effect of nanotubes, the Huh7 cell line, derived from hepatocyte cellular carcinoma cells and serving as a model of human liver, was employed.

2. Materials and methods

2.1. Synthesis of Ni and Ni@Au nanotubes

Nickel nanotubes (Ni NT) were synthesized using a template synthesis method [16, 17, 21, 25, 27]. Ion-track membranes (TM) based on polyethylene terephthalate (PET) with a thickness of 12 μm , a nominal pore diameter of ~ 500 nm, and a density of $1 \cdot 10^7 \text{ cm}^{-2}$ were used as templates. In contrast to the methodology outlined in [21, 25, 27], which involved sputtering Ni on one side of the template, a resistive sputtering technique was employed (Universal Vacuum Post SAHA, Danaengineering) to deposit a copper layer with a thickness of 50 nm on the template surface. The copper layer served as the working electrode (cathode) and could be selectively removed to securely extract Ni NTs from the template. After deposition, the pores remained open, facilitating preferential metal deposition along the pore walls and the formation of nanotube-like nanostructures.

Electrochemical deposition inside the PET TM pores was carried out in a potentiostatic mode at a voltage of 1500 mV. Deposition was conducted from a Watts-type electrolyte with the following composition: $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$ (300 g/l), $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ (45 g/l), H_3BO_3 (38 g/l), at a temperature of 60 °C for 100 s. After the deposition of Ni NT, the copper underlayer was removed by immersing the samples in a solution with the following composition: citric acid (300 g/l), 3% hydrogen peroxide (250 ml/l), NaCl (5 g/l). In the final step, the polymer TM was dissolved in a 6N NaOH solution at 80 °C for 3 h. After complete dissolution of the TM, the nanotubes were washed with distilled water while holding them in place with a magnet.

The synthesis of Ni and Ni@Au NTs was monitored using optical inspection microscopy (Nikon LV100, Japan) with Nikon Element D software in bright-field and dark-field modes (Fig. 1a), and scanning electron microscopes Hitachi TM4000Plus II (Fig. 1c) and JEOL JCM-6000 (Fig. 1d). Energy-dispersive analysis (EDA) was performed using a scanning electron microscope JEOL JCM-6000 (Fig. 1e–g). Transmission electron microscopy images were obtained using Libra-120 (Carl Zeiss, Germany) (Fig. 1b).

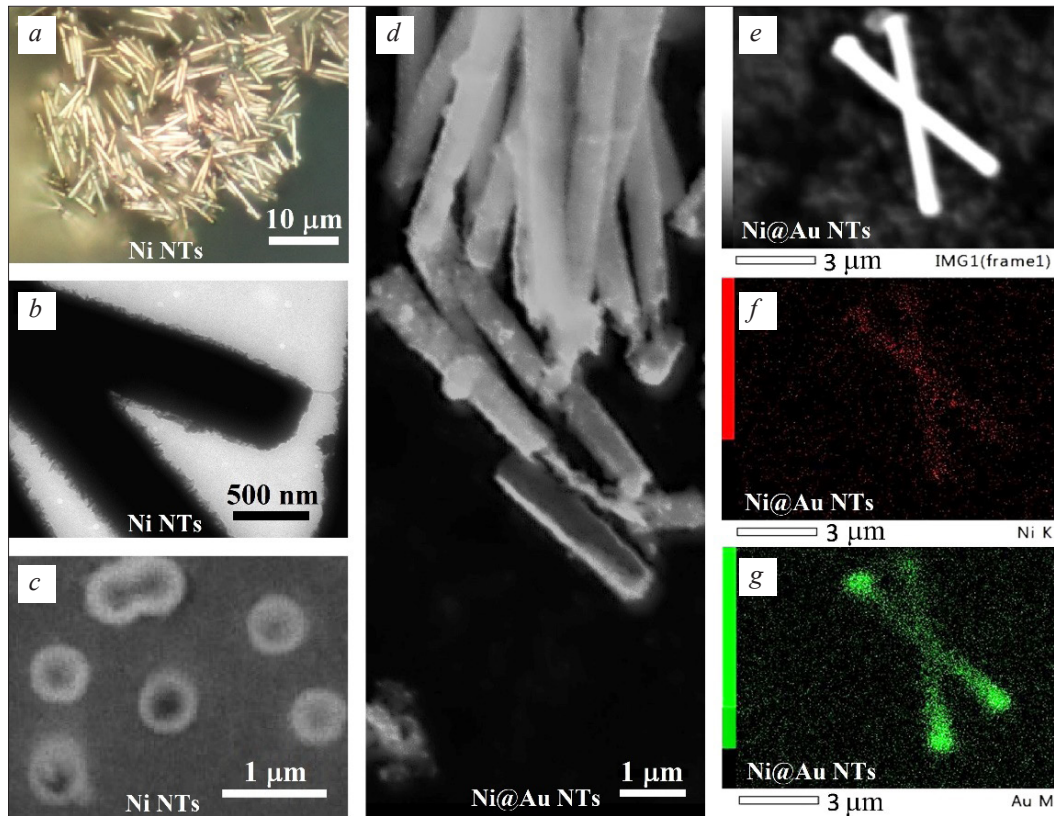


Figure 1. Synthesized NTs. Uncoated Ni NTs: (a) microphotography, (b) TEM image, (c) SEM image of a cross-section of Ni NTs in TM. Coated Ni@Au NTs: (d) SEM image, (e–g) EDA – elemental mapping with selected areas: (f) nickel, (g) gold

Gold coating was carried out in an aqueous solution of AuCl_3 . To do this, a powder of nickel nanotubes weighing no more than 20 mg was placed in 5 ml of a 1% HF solution, and then 5 ml of a 0.01 M aqueous solution of AuCl_3 was added. The deposition process was carried out for 5 min with constant shaking until the solution became clear.

2.2. Magnetic investigations

To measure the magnetic properties, samples were prepared in the form of powders. To do this, the Ni and Ni@Au NTs were suspended in distilled water, and then dried until all the water had evaporated. The resulting NTs powder was placed in a measurement cuvette. It is worth noting that the gold coating significantly prevented the agglomeration of the NTs. Measurements were conducted using a vibrating-sample magnetometer (BM-07) with a range of magnetic field intensity up to 1 T. The measurements were conducted multiple times and subsequently averaged.

To assess the applicability of Ni@Au NTs for magneto-mechanical effects, the change in their orientation in an external magnetic field was studied. This was done by measuring the intensity of light passing through the sample with the Ni@Au NTs suspension in water at parallel and perpendicular orientations of the DC magnetic field relative to the direction of laser beam propagation. The difference in the transmitted intensity is due to a larger

scattering cross-section when the tubes are oriented perpendicular to the laser beam propagation.

2.3. Modeling optical polarizability

The theory of electromagnetic field scattering by layered particles with cylindrical symmetry is well developed [28]. However, a solution in a practically important approximation can be obtained in a convenient form when the absorption inside the particle is taken into account (e.g., in metallic layers) while neglecting time delay effects, which means that the size of the particle should be smaller than the wavelength in the medium. This approach allows for the determination of the particle's polarizability, which is useful for estimating the effective permittivity of the composite. For an infinite cylinder and an electric field perpendicular to the axis, the problem reduces to a two-dimensional solution of Maxwell's equations. In the external space, the field is found in the dipole approximation. The cross-section of the N-layered cylinder is shown in Fig. 2, which also provides the parameters used. In each layer with a dielectric permittivity of ϵ_i , the electric field $\mathbf{E}$ satisfies the equation:

$$\Delta \mathbf{E} + k_i^2 \mathbf{E} = 0; \quad k_i = \frac{\omega}{c} \sqrt{\epsilon_i}, \quad i = 1, \dots, N. \quad (1)$$

Equation (1) is conveniently solved using the vector potential for electric field determination: $\mathbf{E} = \text{curl } \mathbf{A}$, where $\mathbf{A}$ also satisfies Eq. (1). Since $\mathbf{E}$ is an axial vector,

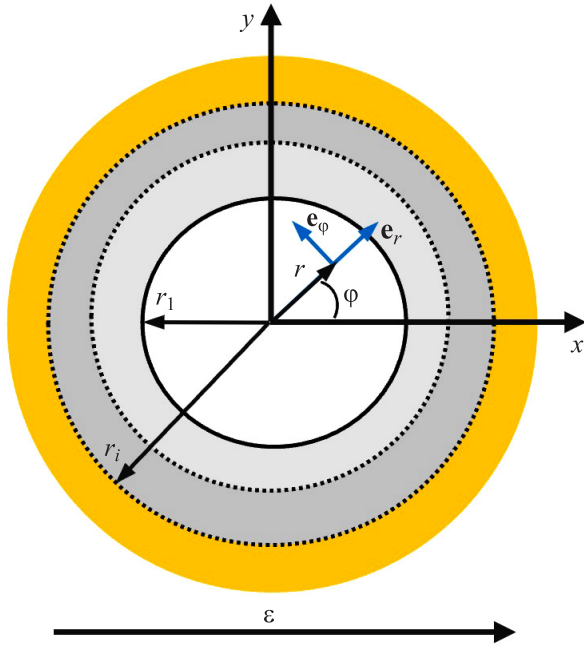


Figure 2. Cross-section of the N-layered cylinder (perpendicular to the axis) with parameters used for calculation. r_i is the radius of the i -th layer. The x -axis is along the external electric field $\mathbf{E}$. $\mathbf{e}_r$, $\mathbf{e}_\phi$ are polar coordinates unit vectors

$\mathbf{A}$ is a polar vector. Based on the symmetry, the sought solution can depend only on a constant vector, which is the external field $\mathbf{E}$. Then, the solution for $\mathbf{A}$ has the form:

$$\mathbf{A} = \nabla \times (f \mathbf{E}). \quad (2)$$

In cylindrical coordinates (r, ϕ) , function f depends on r only in each layer and satisfies

$$\Delta f_i + k_i^2 f = 0. \quad (3)$$

The solution of Eq. (3) is the linear combination of the Bessel functions of the first J_0 and second Y_0 kinds of order 0 (and later $-J_1$ and Y_1 of order 1 are used):

$$f_i = \beta_{i1} J_0(k_i r) + \beta_{i2} Y_0(k_i r). \quad (4)$$

Electric field $\mathbf{E}$ in the i -th layer has the following form:

$$\begin{aligned} \frac{\mathbf{E}}{\epsilon} = & \beta_{i,1(2)} G_{1(2)}(k_i r) \cos \phi \mathbf{e}_r + \\ & + \beta_{i,1(2)} F_{1(2)}(k_i r) \sin \phi \mathbf{e}_\phi, \end{aligned} \quad (5)$$

where

$$\begin{aligned} G_1(x) &= \frac{J_1(x)}{x}; \quad G_2(x) = \frac{Y_1(x)}{x}; \\ F_1(x) &= \frac{J_1(x)}{x} - J_0(x); \quad F_2(x) = \frac{Y_1(x)}{x} - Y_0(x). \end{aligned}$$

Outside the cylinder, the solution for the field is found using the scalar potential, which satisfies the Laplace's equation. The solution takes the form:

$$\mathbf{E} = \frac{2S_p \alpha}{r^2 \epsilon_{\text{out}}} (2(\mathbf{e}_r \mathbf{E}) \mathbf{e}_r - \mathbf{E}) + \mathbf{E}. \quad (6)$$

In Eq. (6), $S_p = \pi r_N^2$ is the total cross section area, α is the electric polarizability, and ϵ_{out} is the permittivity of the outer space. The first amplitude $\beta_{1,1}$ ($\beta_{1,2} = 0$ since the solution in the center must be finite) is stepped through the layers to the outer space to relate with by matching the tangential E_ϕ and normal ϵE_r components across each boundary.

The parameter α describes the particle's response to the influence of an electric field. In particular, the imaginary part α'' characterizes absorption in the system. It is also possible to introduce the extinction parameter, which is the effective scattering cross-section σ_{eff} . In this case, per unit length of the nanotube, this parameter is determined as:

$$\sigma_{\text{eff}} = 8\pi^2 \frac{(\alpha''(\lambda)) S_p}{\lambda}, \quad (7)$$

where λ is the wavelength.

2.4. Optical properties

Spectral dependencies of the optical density (OD) of the NTs solutions were studied using a setup comprised of a halogen lamp, a chopper (OCV-6300F, Avesta), a monochromator (MS3504i, SOL Instruments) with an avalanche photodiode (APD130A(M), Thorlabs) connected to a lock-in amplifier (SR830, Stanford Research) as the measuring circuit. Data was collected within a wavelength range from 500 to 1000 nm with 2 nm intervals, and each interval was measured 20 times before averaging. According to the Beer–Lambert law, the spectrum of OD could be measured as a logarithm of a ratio of beams intensities transmitted through the probe with NTs solution, $I(\lambda)$, and probe with a solvent only, $I_0(\lambda)$:

$$\text{OD}(\lambda) = -\log_{10} \frac{I(\lambda)}{I_0(\lambda)}. \quad (8)$$

Water solutions containing ferromagnetic nanoparticles of these sizes are inherently unstable and tend to experience sedimentation and agglomeration. To obtain experimental data from solutions of known concentrations (100 $\mu\text{g/ml}$) the NTs solutions were stabilized by adding sodium dodecyl sulfate (SDS, 5 wt.% of water). Additionally, the probes with NTs solutions were placed on a magnetic stirrer. The stirring process was carried out using a soft ferromagnetic anchor covered with a thick polymer layer to prevent the attraction of NTs to it during stirring. The homogeneity of the NTs concentration was confirmed by measuring ODs across the probe. The stability of the solutions was assessed by measuring the OD over time. Prior to each experiment, the NTs solutions

were sonicated and demagnetized using an AC magnetic field with a magnitude of up to 150 mT.

2.5. Photothermal properties

To evaluate the photothermal properties, the NTs solutions were subjected to a laser heating and subsequent cooling. The heating laser diode (L808P1000MM, ThorLabs) with wavelength centered at 806 nm (FWHM = 2 nm) was providing the optical output power of 0.625 W and power density of 2.4 W/cm² (3.5×7.5 mm irradiated area). The laser diode was thermostabilized by a piezoelectric mount (LDM90, ThorLabs). During the photothermal heating the power of the laser beam transmitted through the solutions with and without NTs was measured with a photodiode in an integrating sphere (S142, ThorLabs) and a power-meter console (PM100D, ThorLabs). Cuvettes for the solutions were made of thin glass with inner volume of ~1.9 ml and dimensions 12.5×12.5×12.5 mm. The temperature evolution of the solutions was measured with IR-camera (CG640, COX). The camera was averaging the signal from the side wall of the cuvette. Emissivity of the glass was chosen as 0.89. The cuvettes were securely positioned on a magnetic stirrer at a distance of 1 cm from the top surface to minimize the influence of the magnetic field on NTs. The solvent for the NTs was a water solution of SDS at a concentration of 5 wt.%. Prior to the experiment, the NTs solutions were sonicated for 5 min and thoroughly mixed using a vortex mixer. Subsequently, they were placed in a cuvette, which was sealed with silicone adhesive and a lid. The experimental setup monitored both the changes in temperature and OD of the NTs suspension during laser heating and cooling when the laser was turned off.

The photothermal efficiency of the NTs solutions was assessed using the value of OD at the laser wavelength and the photothermal conversion coefficient. The coefficient indicates the fraction of absorbed radiant energy that is converted into heat and ranges from 0 to 1 (or 0 to 100%). In this work, the coefficient was evaluated using the method which is based on a thermal equilibrium approach [29, 30]. In this model, the heat exchange between the system and the surroundings is described by a time constant, which can be extracted from the temperature change during cooling after turning off the laser. Subsequently, the photothermal conversion coefficient is calculated as the ratio of the heat generated in the sample to the absorbed irradiation energy:

$$\eta = \frac{\sum_i m_i c_i \left(\frac{\Delta T_{\max}}{\tau} - \frac{\Delta T_{\max}^0}{\tau_0} \right)}{P_0 (1-r) \left(1 - \frac{I}{I_0} \right)} \quad (9)$$

In Eq. (9), $\sum_i m_i c_i$ represents the product of heat capacity and mass of each component in the sample with the solution, $\Delta T_{\max}$, $\Delta T_{\max}^0$ is the maximum temperatures reached by the nanoparticle solution and solution without

particles, respectively, when heated to equilibrium temperature, τ , τ_0 are the corresponding heating time constants with and without particles, P_0 is the power of the laser beam incident on the sample, r is the fraction of radiation reflected from the air-cuvette-sample interface, I/I_0 is the transmittance coefficient of the nanoparticle suspension, where I is the intensity of the radiation passing through the cuvette with the NTs solution, and I_0 is the intensity of the radiation passing through the cuvette with the solvent without NTs.

The characteristic time constant of the sample with nanoparticle solution,

$$\tau = \sum_i \frac{m_i c_i}{h},$$

where h is the heat transfer coefficient between the probe with the sample and environment, can be determined from the natural logarithm slope of the relative temperature θ during cooling as $\tau = -1/\ln(\theta)$. To distinguish the heating effects originating from the nanoparticle suspension from those arising due to the absorption of the cuvette with the solvent, an experiment was carried out using only the solvent in the cuvette. In this scenario, the parameters $\Delta T_{\max}^0$ and τ_0 were determined using the same methodology.

2.6. Cytotoxicity analysis

To examine the cytotoxic effect of nanotubes, hepatocyte derived cellular carcinoma cell line (Huh7) obtained from the Japanese Collection of Research Bioresources (JCRB) was used. The Huh7 cell line can be considered as a model of human liver since magnetic nanoparticles tend to accumulate in the liver [31]. The fourth and fifth passages of the Huh7 cell line were used for experiments. Cells were cultured in Dulbecco's Modified Eagle Medium (DMEM, Himedia, USA) completed with fetal bovine serum (Sigma, USA) to a final concentration of 10% and penicillin/streptomycin 1% (Sigma, USA). Cells were incubated in standard conditions: a 5% CO₂ and 37°C humidified atmosphere. Before each experiment cellular survival was checked using Trypan blue staining 0.4% (Invitrogen, USA).

The cytotoxicity was measured using a WST-1 (Roche Diagnostics GmbH, Germany) test after 24 h of exposure with tested NT. Huh7 cells were seeded at a density of 10⁶ cells per ml in 96 well microplates with 100 µl of cell suspension per well. After overnight, when the cells were attached to the wells surface, 100 µl of fresh DMEM with NTs in 10, 50 and 100 µg/ml concentrations were added to wells. The control wells were prepared in the absence of nanomaterials. Each experiment was conducted six times independently. During the last 2 h of exposure, 10 µl of WST-1 reagent was added. The OD was measured at 450 nm using a Multiskan FC microplate reader by Thermo Scientific. All cytotoxicity results were obtained by subtraction of blank wells (without cells) absorbance from experimental wells'

absorbance to eliminate the influence of nanoparticles and cell medium.

After 24 h of exposure of cell samples with Ni NTs and Ni@Au NTs at different concentrations optical microscopy images were taken at $\times 40$ magnification using an inverted microscope CKX53 (Olympus, Japan).

2.7. Photothermal therapy

Huh7 cell culture was used to define the efficiency of NTs photothermal therapy. Before the experiment, cells were pre-cultivated in 96 well plate as it was described in section 2.6. Once the cells had attached to the wells, the medium of experimental wells was replaced with Ni@Au NTs DMEM suspension at a concentration of 50 $\mu\text{g/ml}$. The medium of control wells was replaced by complete DMEM and whole plate was incubated for 24 h on standard conditions. Each photothermal treatment was conducted four times for control and experimental wells with volume of 100 μl . During the photothermal treatment, other 96-well plate with Control probes, the 50 $\mu\text{g/ml}$ experimental samples and blank probes for all groups was left in standard incubation conditions.

The in vitro photothermal heating was carried out using the same heating setup used to evaluate the photothermal performance of NTs. The laser, the infrared (IR) camera, and the 96-well plate holder were placed in a thermostatic cabinet, maintaining a temperature of approximately 37°C. The laser output optical power was 0.6 W, with a power density of 2.4 W/cm² (for a 5×5 mm irradiated area). The IR camera recorded signals from the bottom of each irradiated well. Each heating cycle lasted 30 min.

Following the photothermal therapy, all samples were stained with 10 μl of WST-1 reagent and incubated for one hour under standard conditions. OD measurements were performed as described in section 2.6.

2.8. Statistical analysis

All cytotoxicity results before and after photothermal therapy were presented as the mean and standard deviation. To compare each group to the control group, the nonparametric Kruskal-Wallis test with GraphPad Prism v.7.04 was used.

3. Results and discussion

3.1. Structural characterization

Figure 1 shows an optical microphotograph (see Fig. 1a) and a TEM image (see Fig. 1b) of the obtained Ni NTs. The SEM image of cross-sections of Ni NTs was performed on the undissolved TM with NTs in its pores (see Fig. 1c), allowing for the determination of the inner diameter. It is seen that the Ni NTs are hollow structures with an outer

diameter corresponding to the template pore diameter of $\sim 520 \pm 20$ nm, an inner diameter of $\sim 320 \pm 10$ nm, and wall thickness of $\sim 100 \pm 10$ nm. The length of the nanotubes is 7.5 ± 0.3 μm .

Ni@Au NTs powder consists of individual structures that may agglomerate over time. In the SEM image (see Fig. 1d), Ni@Au NTs are shown with their surfaces entirely covered by a layer of gold with sporadic gold crystal inclusions, forming periodic protrusions on the surface. Some thickening is noticeable at the ends of the nanotubes (see Fig. 1e), where a denser layer of gold is formed. The external diameter of Ni@Au NTs measures approximately $\sim 640 \pm 20$ nm, which corresponds to a gold layer thickness of around 60 nm. After gold coating, the inner cavity of the nanotubes is clearly distinguishable on tube fractures, indicating that the inner channel of the tube remains unoccupied after coating. According to energy-dispersive analysis (EDA), the ratio of nickel to gold is 34:66 (wt.%) (see Fig. 1f and Fig. 1g). The thickness of the gold layer and the elemental composition data suggest the formation of a dense gold layer, which prevents the degradation of nickel NTs and promotes their biological compatibility [25].

NTs have relatively large dimensions for bioapplications. However, the outer diameter can be reduced down to 100–200 nm, producing nanotubes with a wall thickness of 20–40 nm [16]. The length of NTs can also be decreased by adjusting the growth time. A relatively large pore diameter was chosen to experimentally confirm the mechanical responsiveness of NTs to an external magnetic field by optical methods. Additionally, we can anticipate that proportional changes in dimensions will not qualitatively alter the magnetic properties.

3.2. Magnetic properties

Nickel nanotubes, which are positioned within a template and have a strict orientation, exhibit a pronounced magnetic anisotropy, with the axis of easy magnetization aligning with the nanotube axis [27]. In this work, the magnetization behavior of NTs extracted from the template was of interest. Figure 3a illustrates the hysteresis loops of powder samples of Ni NTs and Ni@Au NTs. The hysteresis loops are almost identical but the coercivity H_c and remanence magnetization for Ni NTs are lower. The ratio of remanence magnetization to saturation is close to 0.5 (in particular, for Ni@Au NTs), which corresponds to the chaotic arrangement in the powder sample of nanotubes with axial anisotropy. The coercive force H_c is approximately 20 kA/m, and the saturation field is above 200 kA/m, which is close to the value of the demagnetizing field for a uniformly magnetized cylinder $H_d = M_s/2$ (for Ni the saturation magnetization $M_s = 4.9 \cdot 10^5$ A/m).

Next, the influence of a magnetic field on the orientation of nanotubes in solution was studied. It can be assumed that a small magnetic field H , significantly lesser than H_c , does not lead to a change in the magnetization direction inside the tubes. In this case, NT will rotate in

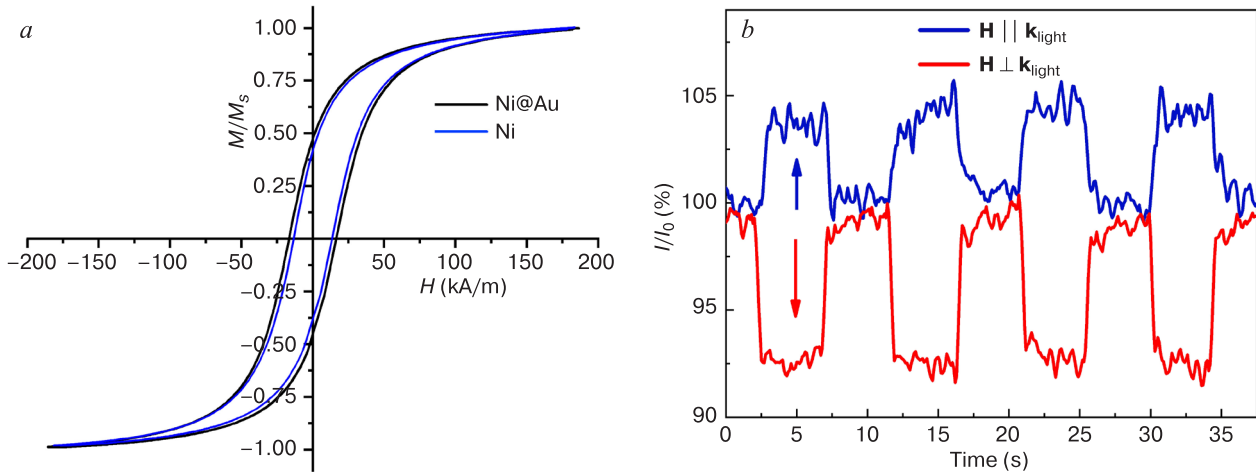


Figure 3. (a) Hysteresis loops of powder samples of Ni NTs and Ni@Au NTs, (b) changes in the relative intensity of light transmitted through the solution of Ni@Au NTs when a static isotropic magnetic field of 6.4 kA/m is switched on and off, directed either parallel (blue curve) or perpendicular (red) to the beam of light, is shown in the plot. The optical intensity is normalized with respect to the signal level in the absence of a magnetic field, I_0 . The NTs solution was placed on a magnetic stirrer as described in section 2.4

the direction of the field under the influence of the torque. The change in the angle β between the NT axis and the magnetic field H is described by the following equation:

$$FV\eta \frac{d\beta}{dt} = \mu_0 m_p H \sin \beta. \quad (10)$$

In Eq. (10) m_p is a magnetic moment of NT, μ_0 is the permittivity of vacuum, η is the dynamic viscosity of liquid, V is the NT volume and F is the shape factor. For $m_p = 0.1M_s V_m$, V_m is the volume of Ni portion of NT, $H = 80$ A/m, $\eta = 10^{-3}$ Pa·s (viscosity of water) the characteristic frequency below which the particle follows the field without lag is approximately 195 Hz. The maximum applied force can be estimated from the maximum magnetic torque using the formula $f = 2\mu_0 m_p H/l$, where l represents the nanotube length. For the parameters used, this force is approximately 5 pN. If the magnetic moment increases, which can be influenced by remanence magnetization, or an applied field is higher (for example, $H = 8$ kA/m is still lower than the coercivity), the force could increase to the order of 100s of pN. This level of force might be sufficient to potentially rupture the cell membrane [11, see also Supplementary]. Even smaller forces, however, can lead to the formation of pores in the membrane [32].

NTs coated with gold exhibit a relatively large scattering cross-section, which depends on their orientation with respect to the incident light beam due to polarization effect. The scattering cross-section is larger when the electric field is along the tube axis, that is, when the tube is oriented perpendicularly to the light beam propagation. This can be used to experimentally confirm the mechanical responsiveness of NTs to an external magnetic field. When in a solution, the tubes are randomly oriented if there is no external field applied. However, upon the application of a magnetic field parallel to the laser beam direction, the tubes partially align along the wavevector $\mathbf{k}$, with the electric field perpendicular to their axis.

This alignment results in a reduction of the light scattering cross-section, leading to a slight increase in transmitted light intensity. Conversely, applying a magnetic field perpendicular to the laser beam causes the partial alignment of NTs across the radiation propagation, leading to an increase in the scattering cross-section and a subsequent decrease in intensity. The alteration in transmitted light intensity through a solution of Ni@Au NTs (5 wt.% aqueous SDS solution) is illustrated in Fig. 3b. A DC homogeneous magnetic field, denoted as H , was alternately switched on and off, with two orientations relative to the direction of $\mathbf{k}$. Due to the conserved magnetic properties of nanotubes despite their gold layer coverage, as depicted in Fig. 3a, it is anticipated that their magnetic dynamics within a magnetic field would resemble that observed for Ni@Au NTs.

3.3. Optical properties

Figure 4a shows a comparison of the imaginary part of polarizability α'' for Ni NTs and Ni@Au NTs. The data for the dielectric constants of gold and nickel were taken from references [33, 34]. When a layer of gold is added, a resonance peak appears. It is worth noting that the positions of the resonance peaks depend not only on the thickness of the golden layer but also on the thickness of the nickel NT walls. There is a trend to a redshift in the resonance lines observed as both the thickness of the nickel walls and the thickness of the gold layer increase. For Ni@Au NTs in water with an internal diameter of 300 nm, a nickel thickness of 100 nm, and a gold layer thickness of 50 nm, the resonance wavelength is 730 nm. It is anticipated that the resonance peaks will undergo a further redshift as the thickness of the gold layer increases. Given the relatively large dimensions of the structures under consideration, it is important to account for time-delay effects in the long-wavelength range, as these effects lead to an increase in the effective absorption

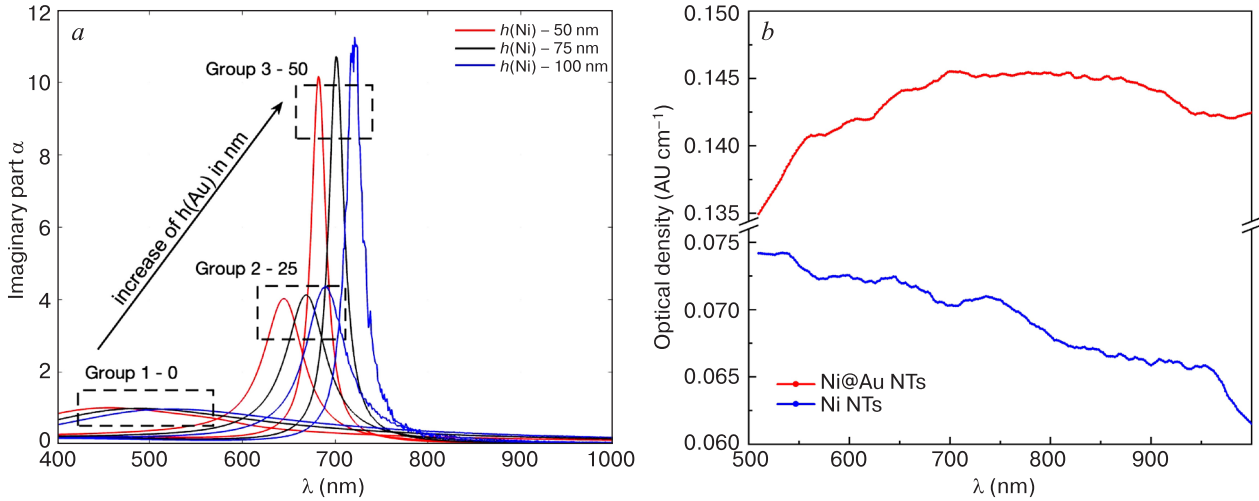


Figure 4. (a) Calculated spectra of the imaginary part of electric polarizability α of Ni NTs and Ni@Au NTs for different thickness of nickel and gold layers with inner diameter (hollow part) of 300 nm. Nickel layer thickness – 50 (red curves), 75 (black curves), and 100 nm (red curves); the groups 1–3 of spectra from left to right are for the Au layer thickness of 0, 25, and 50 nm, respectively. As the Au layer thickness increases, the peak values progressively rise, and the plasmon resonance wavelength shifts towards the infrared region. The dielectric susceptibility of medium (water) – $\epsilon_{\text{out}} = 1.7$, data for complex-valued permittivity of gold and nickel were taken from references [33, 34], (b) experimental OD spectra of Ni NTs (blue curve) and Ni@Au NTs (red curve) in a 5% aqueous SDS solution. The concentration of NTs was 100 $\mu\text{g/ml}$

and scattering cross-sections. A larger and non-resonant scattering cross-section will occur when the polarization aligns with the electric field along the tube axis. Consequently, the experimental spectra are expected to be significantly broader, as shown in Fig. 4b.

The experimental OD spectra of Ni NTs and Ni@Au NTs solutions at concentration of 100 $\mu\text{g/ml}$ presented in Fig. 4b were calculated using Eq. (8). The Ni NTs solution generally shows a decrease in OD with increasing wavelength, which is typical for many magnetic nanoparticles (e.g., iron oxide ferrites). Addition of a golden layer increases the OD of the Ni@Au NTs solution at all wavelengths by approximately 2 times. Additionally, a broad peak appears with the center at ~ 750 nm. The maximum position aligns with the theoretical model, considering that the average measured thickness of the gold layer in the obtained Ni@Au NTs is slightly higher than 50 nm. Golden coverage thickness variations on individual NTs or NTs agglomeration can also contribute to the broadening of the peak. The substantial increase in OD and the presence of a resonant maximum near the wavelength used in photothermal therapy support the enhanced utility of such nanoparticles in photothermal therapy.

3.4. Photothermal properties

Figure 5 displays the results of photothermal heating of aqueous solutions of Ni NTs and Ni@Au NTs at concentrations of 100 $\mu\text{g/ml}$. Each curve represents the average of five repetitions. The photothermal heating of NTs solutions relative to the maximum solvent temperature without particles amounted to approximately 2 K and 5.7 K for Ni NTs and Ni@Au NTs, respectively. Similarly, the ODs of the solutions measured during the experiments

were found to be 0.063 and 0.147 AU cm⁻¹, respectively, which approximately corresponds to ODs at a wavelength of ~ 806 nm, obtained during spectroscopic measurements. The characteristic cooling time, calculated from the temperature curves when the laser was turned off, was approximately 715 ± 10 s (see Supplementary S1). The calculated photothermal conversions of Ni NTs and Ni@Au NTs solutions using Eq. (9) were 27.0 ± 3.0 % and 38.0 ± 1.6 %, respectively. Thus, in addition to increasing optical absorption, the gold coating of particles also enhances the photothermal efficiency coefficient, further increasing the maximum heating temperature. These val-

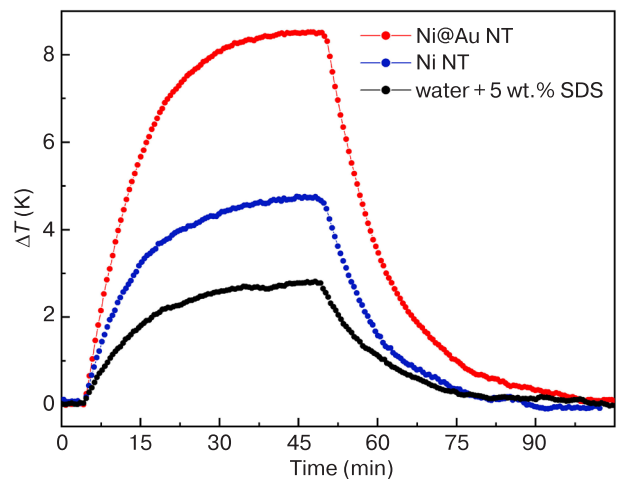


Figure 5. Temperature changes relative to the initial temperature during photothermal heating and subsequent cooling (laser turned off) of Ni NTs (blue curve), Ni@Au NTs (red curve), and a 5% aqueous SDS solution (black curve). The concentration of NTs was 100 $\mu\text{g/ml}$. Each curve represents the result of averaging five repetitions

ues are in line with those for spherical gold particles with diameters larger than 50 nm and gold nanotubes with diameters larger than 20 nm [23]. Therefore, gold-coated NTs have the potential to be used in photothermal therapy. Considering the magnetic properties of Ni NTs, it is possible to conduct combined magneto-mechanical and photothermal therapies.

3.5. Biocompatibility of Ni NTs and Ni@Au NTs

From the experience of working with magnetic nanomaterials, three reference concentrations of nanotubes were chosen: 10, 50 and 100 $\mu\text{g/ml}$, which is within the range of the most commonly used concentrations of nanomaterials in biomedicine [31–32]. After exposure for 24 h optical microscopy images of cells with NTs in different concentrations were obtained (see Supplementary S2). It was shown that NTs precipitate during exposure and settle on the surface of the cells and the bottom of the well. It can be seen that NTs are distributed in the samples both in the form of agglomerates and as individual particles, which will make it possible to effectively use these types of materials for magnetomechanical therapy.

The test results presented in Fig. 6 showed a statistically significant decrease in the viability of Huh7 cells when the concentration was increased to 50 $\mu\text{g/ml}$, the number of living cells was decreased to 64%, and at a concentration of 100 $\mu\text{g/ml}$ it was decreased to 24% compared to the control group. In the work of Ahmad et al. [35], the cytotoxicity of nickel nanoparticles to human liver (HepG2) cells is at a similar level and cells viability was 81, 66, and 52% at concentrations of 25, 50, and 100 $\mu\text{g/ml}$, respectively. The authors explain this result by the generation of ROS leading to cell death. This tendency is understandable for nanomaterials containing nickel, which cause adverse effects on human health [36–39]. After coating Ni NTs with gold, no statistically proven cytotoxic effect for concentration 10 $\mu\text{g/ml}$ was observed. For a concentration of 50 $\mu\text{g/ml}$ viability

amounted to 62% and decreased to 39% at 100 $\mu\text{g/ml}$ compared to uncoated NT (see Fig. 6). While statistical significance for the decrease in cytotoxicity at lower concentrations was not established, there is a discernible trend suggesting the presence of a gold-mediated effect when compared to control sample. However, the toxicity effect remains significant for cells. This could be due to large particle size and uneven gold coating with thickening at the ends. Further investigation on improvements of biocompatibility is required.

3.6. Photothermal therapy of Ni@Au NTs in vitro

An experiment was also conducted to test photothermal therapy in vitro for Ni@Au NTs at a concentration of 50 $\mu\text{g/ml}$. On the one hand, it was necessary to choose the highest concentration to increase the achievable heating of the samples. On the other hand, the concentration should not be high due to the cytotoxicity of the sample. For these reasons a concentration of 50 $\mu\text{g/ml}$ was chosen. The results showed that exposing cells without NTs did not affect cell culture viability. However, there was no significant difference between cell viability with and without treatment on samples with Ni@Au NT at a concentration used. Maximum temperature during therapy reached 40.4 $^{\circ}\text{C}$ (see Supplementary S3), which is insufficient to induce a negative effect on cells (see Supplementary S4). Thus, to achieve the result of photothermal therapy, it is necessary to optimize the characteristics of the NTs and to vary the thickness of golden coating as well as the nanotubes dimensions.

4. Conclusions

Ni NTs with an outer diameter of 500 nm, wall thickness of approximately 100 nm, and a length of around 7.5 μm were synthesized using the template method. Some of these nanotubes were coated with gold, with an average

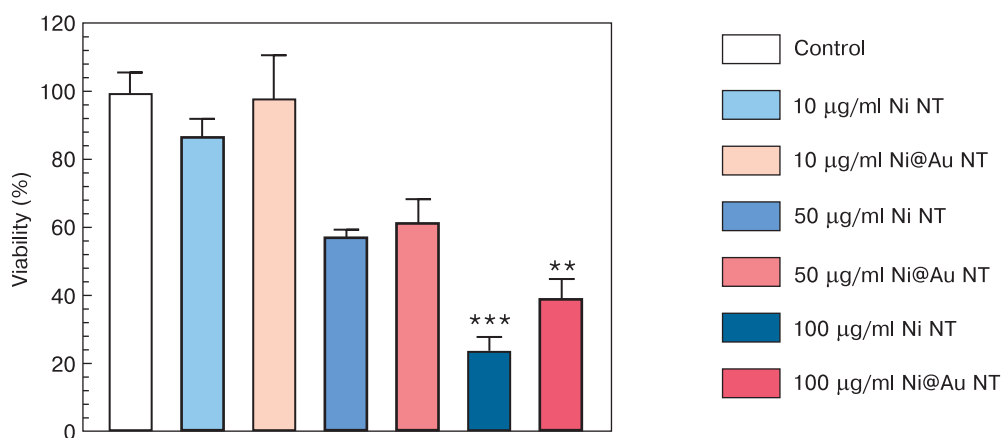


Figure 6. Viability of Huh7 cell line after 24 h treatment with 10, 50, and 100 $\mu\text{g/ml}$ suspension of Ni NTs (blue) and Ni@Au NTs (red). Cell viability was tested by WST-1 assay. All results are normalized by control and columns denoted by asterisks indicate results that were statistically different from the control. Control well was with the absence of NT. Statistical significance levels between experimental and control groups are presented by asterisks (** for p value <0.0021 , *** for p value <0.0002)

thickness of 60 nm and some thickening at the ends. The magnetic and optical properties of such structures were investigated both theoretically and experimentally.

Possessing significant magnetic anisotropy, with the axis of easy magnetization coinciding with the axis of the nanotubes, individual nanotubes can be oriented using an external magnetic field. Therefore, through the magneto-mechanical effect, these nanotubes can interact with biological entities in an alternating magnetic field.

A theoretical model has been proposed to describe the dielectric properties of nickel nanotubes with and without gold coating. The presence of a resonance peak in the interaction with electromagnetic fields in the red and near-infrared regions of the spectrum has been demonstrated upon adding a layer of gold. A redshift of the resonance peaks has been observed with increasing thickness, both of the gold layer and the nickel walls of the nanotubes.

The results of theoretical modeling are in good agreement with the measured OD spectra of Ni NTs and Ni@Au NTs solutions. The OD amplitudes for structures with gold coating are approximately twice as large as those for uncoated tubes, and they exhibit a broad absorption band within the 700–900 nm range. As a result, the photothermal properties of gold-coated Ni NTs are enhanced. The photothermal conversion coefficient increased from $27.0 \pm 3.0\%$ (for Ni NTs) to $38.0 \pm 1.6\%$ (for

Ni@Au NTs), with a two-fold increase in the temperature rise.

For the obtained NTs the gold coating did not significantly reduce the toxicity. This could be attributed to a large particle size and uneven gold coating. Further investigation into enhancing biocompatibility is imperative. For a Ni@Au NTs concentration of 50 mg/ml, the cell viability exceeded 60% making this concentration suitable for the photothermal investigations. However, the maximum temperature reached during therapy was 40.4°C , which was insufficient for inducing cell death. Higher concentration of NTs are needed for a more effective outcome.

Acknowledgments

This work was funded by the Russian Science Foundation, grant No. 21-72-20158.

For transmission electron microscopy studies we thank A.M. Burov, senior engineer of the CCU “Simbioz” (IBPPM RAS, Saratov, Russia) and Vitaly Khanadeev, senior researcher of Institute of Biochemistry and Physiology of Plants and Microorganisms (IBPPM RAS, Saratov, Russia) and Saratov State University of Genetics, Biotechnology and Engineering named after N.I. Vavilov (Saratov, Russia).

References

1. Pankhurst Q.A., Connolly J., Jones S.K., Dobson J. Applications of magnetic nanoparticles in biomedicine. *Journal of Physics D: Applied Physics*. 2003; 36(13): R167–R181. <https://doi.org/10.1088/0022-3727/36/13/201>
2. Dutz S., Hergt R. Magnetic particle hyperthermia – A promising tumour therapy? *Nanotechnology*. 2014; 25(45): 452001. <https://doi.org/10.1088/0957-4484/25/45/452001>
3. Kafrouni L., Savadogo O. Recent progress on magnetic nanoparticles for magnetic hyperthermia. *Progress in Biomaterials*. 2016; 5(3-4): 147–160. <https://doi.org/10.1007/s40204-016-0054-6>
4. Nguyen T.L., Nizamov T.R., Abakumov M.A., Shchetinin I.V., Savchenko A.G., Majouga A.G. Effect of magnetite nanoparticle morphology on the parameters of MRI relaxivity. *Bulletin of the Russian Academy of Sciences: Physics*. 2018; 82(9): 1214–1221. <https://doi.org/10.3103/S1062873818090150>
5. Kasyanenko E.M., Omelchenko A.I., Sobol E.N. Photothermal effect of laser exposure on the electrical properties of cartilage tissue with magnetite nanoparticles. *Bulletin of the Russian Academy of Sciences: Physics*. 2016; 80(4): 463–466. (In Russ.). <https://doi.org/10.7868/S0367676516040177>
6. Janssen X.J.A., Schellekens A.J., Van Ommering K., Jzendoorn L.J., Van I., Prins M.W.J. Controlled torque on superparamagnetic beads for functional biosensors. *Biosensors and Bioelectronics*. 2009; 24(7): 1937–1941. <https://doi.org/10.1016/j.bios.2008.09.024>
7. Maniotis N., Makridis A., Myrovali E., Theopoulos A., Samaras T., Angelakeris M. Magneto-mechanical action of multimodal field configurations on magnetic nanoparticle environments. *Journal of Magnetism and Magnetic Materials*. 2019; 470: 6–11. <https://doi.org/10.1016/j.jmmm.2017.12.024>
8. Shen Y., Wu C., Uyeda T.Q.P., Plaza G.R., Liu B., Han Y., Lesniak M.S., Cheng Y. Elongated nanoparticle aggregates in cancer cells for mechanical destruction with low frequency rotating magnetic field. *Theranostics*. 2017; 7(6): 1735–1748. <https://doi.org/10.7150/thno.18352>
9. Fung A.O., Kapadia V., Pierstorff E., Ho D., Chen Y. Induction of cell death by magnetic actuation of nickel nanowires internalized by fibroblasts. *The Journal of Physical Chemistry C*. 2008; 112(30): 15085–15088. <https://doi.org/10.1021/jp806187r>
10. Contreras M., Sougrat R., Zaher A., Ravasi T., Kosel J. Non-chemotoxic induction of cancer cell death using magnetic nanowires. *International Journal of Nanomedicine*. 2015; 10(1): 2141–2153. <https://doi.org/10.2147/IJN.S77081>
11. Kim D.-H., Rozhkova E.A., Ulasov I.V., Bader S.D., Rajh T., Lesniak M.S., Novosad V. Biofunctionalized magnetic-vortex microdisks for targeted cancer-cell destruction. *Nature Materials*. 2010; 9(2): 165–171. <https://doi.org/10.1038/nmat2591>
12. Novosad V., Rozhkova E.A. Ferromagnets-based multifunctional nanoplatform for targeted cancer therapy. In: Laskovski A. (ed.). *Biomedical engineering, trends in materials science*. InTech; 2011. P. 425–444. <https://doi.org/10.5772/12928>
13. Mengwei Ch., Wu J., Ning P., Wang J., Ma Z., Huang L., Plaza G.R., Shen Y., Xu C., Han Y., Lesniak M.S., Liu Z., Cheng Y. Remote control of mechanical forces via mitochondrial-targeted

- magnetic nanospinners for efficient cancer treatment. *Small*. 2020; 16(3): 1905424. <https://doi.org/10.1002/sml.201905424>
14. Martínez-Banderas A.I., Aires A., Teran F.J., Perez J.E., Cadenas J.F., Alsharif N., Ravasi T., Cortajarena A.L., Kosel J. Functionalized magnetic nanowires for chemical and magneto-mechanical induction of cancer cell death. *Scientific Reports*. 2016; 6: 35786. <https://doi.org/10.1038/srep35786>
 15. Wong D.W., Gan W.L., Liu N., Lew W.S. Magneto-actuated cell apoptosis by biaxial pulsed magnetic field. *Scientific Reports*. 2017; 7(1): 10919. <https://doi.org/10.1038/s41598-017-11279-w>
 16. Shumskaya A., Bundyukova V., Kozlovskiy A., Zdorovets M., Kadyrzhanov K., Kalkabay G., Kaniukov E. Evolution of morphology, structure, and magnetic parameters of Ni nanotubes with growth in pores of a PET template. *Journal of Magnetism and Magnetic Materials*. 2020; 497: 165913. <https://doi.org/10.1016/j.jmmm.2019.165913>
 17. Zagorskiy D., Doludenko I., Zhigalina O., Khmelenin D., Kanevskiy V. Formation of nanowires of various types in the process of galvanic deposition of iron group metals into the pores of a track membrane. *Membranes*. 2022; 12(2): 195. <https://doi.org/10.3390/membranes12020195>
 18. Narayanan T.N., Shajumon M.M., Ajayan P.M., Anantharaman M.R. Synthesis of high coercivity cobalt nanotubes with acetate precursors and elucidation of the mechanism of growth. *The Journal of Physical Chemistry C*. 2008; 112(37): 14281–14285. <https://doi.org/10.1021/jp8035007>
 19. Cheng Y., Morshed R.A., Auffinger B., Tobias A.L., Lesniak M.S. Multifunctional nanoparticles for brain tumor imaging and therapy. *Advanced Drug Delivery Reviews*. 2014; 66: 42–57. <https://doi.org/10.1016/j.addr.2013.09.006>
 20. Efremova M.V., Naumenko V.A., Spasova M., Garanina A.S., Abakumov M.A., Blokhina A.D., Melnikov P.A., Prelovskaya A.O., Heidelmann M., Li Z.-A., Ma Z., Shchetinin I.V., Golovin Y.I., Kireev I.I., Savchenko A.G., Chekhonin V.P., Klyachko N.L., Farle M., Majouga A.G., Wiedwald U. Magnetite-gold nanohybrids as ideal all-in-one platforms for theranostics. *Scientific Reports*. 2018; 8(1): 11295. <https://doi.org/10.1038/s41598-018-29618-w>
 21. Panina L.V., Belyaev V.K., Anikin A., Shumskaya A., Kozlov A.G., Ognev A.V., Rogachev A., Korol'kov I., Zdorovets M., Kozlovskii A., Rodionova V.V. Nanocomposites with magnetic core-gold shell structure for photothermia. *Physics of Metals and Metallography*. 2022; 123: 1185–1192. <https://doi.org/10.1134/S0031918X22601597>
 22. Vines J.B., Yoon J.-H., Ryu N.-E., Lim D.-J., Park H. Gold nanoparticles for photothermal cancer therapy. *Frontiers in Chemistry*. 2019; 7: 167. <https://doi.org/10.3389/fchem.2019.00167>
 23. Ali M.R.K., Wu Y.J., El-Sayed M.A. Gold-nanoparticle-assisted plasmonic photothermal therapy advances toward clinical application. *The Journal of Physical Chemistry C*. 2019; 123(25): 15375–15393. <https://doi.org/10.1021/acs.jpcc.9b01961>
 24. Shi X., Tian Y., Liu Y., Xiong Z., Zhai S., Chu S., Gao F. Research progress of photothermal nanomaterials in multimodal tumor therapy. *Frontiers in Oncology*. 2022; 12: 939365. <https://doi.org/10.3389/fonc.2022.939365>
 25. Shumskaya A., Korolkov I., Rogachev A., Ignatovich Zh., Kozlovskiy A., Zdorovets M., Anisovich M., Bashouti M., Shalabny A., Busool R., Khubezhov S., Yakimchuk D., Bundyukova V., Panina L.V., Kaniukov E. Synthesis of Ni@Au core-shell magnetic nanotubes for bioapplication and SERS detection. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2021; 626: 127077. <https://doi.org/10.1016/j.colsurfa.2021.127077>
 26. Hemmer E., Benayas A., Légaré F., Vetrone F. Exploiting the biological windows: Current perspectives on fluorescent bioprobes emitting above 1000 nm. *Nanoscale Horizons*. 2016; 1(3): 168–184. <https://doi.org/10.1039/C5NH00073D>
 27. Kozlovskiy A.L., Korolkov I.V., Kalkabay G., Ibragimova M.A., Ibrayeva A.D., Zdorovets M.V., Mikulich V.S., Yakimchuk D.V., Shumskaya A.E., Kaniukov E.Y. Comprehensive study of Ni nanotubes for bioapplications: From synthesis to payloads attaching. *Journal of Nanomaterials*. 2017; 2017(23): 3060972. <https://doi.org/10.1155/2017/3060972>
 28. Kim C.S., Yeh C. Scattering of an obliquely incident wave by a multilayered elliptical lossy dielectric cylinder. *Radio Science*. 1991; 26(05): 1165–1176. <https://doi.org/10.1029/91RS01706>
 29. Roper D.K., Ahn W., Hoepfner M. Microscale heat transfer transduced by surface plasmon resonant gold nanoparticles. *The Journal of Physical Chemistry C*. 2007; 111(9): 3636–3641. <https://doi.org/10.1021/jp064341w>
 30. Chen H., Shao L., Ming T., Sun Z., Zhao C., Yang B., Wang J. Understanding the photothermal conversion efficiency of gold nanocrystals. *Small*. 2010; 6(20): 2272–2280. <https://doi.org/10.1002/sml.201001109>
 31. Mailänder V., Landfester K. Interaction of nanoparticles with cells. *Biomacromolecules*. 2009; 10(9): 2379–2400. <https://doi.org/10.1021/bm900266r>
 32. Suresh S. Biomechanics and biophysics of cancer cells. *Acta Biomaterialia*. 2007; 3(4): 413–438. <https://doi.org/10.1016/j.actbio.2007.04.002>
 33. Johnson P.B., Christy R.W. Optical constants of the noble metals. *Physical Review B*. 1972; 6: 4370–4379. <https://doi.org/10.1103/PhysRevB.6.4370>
 34. Johnson P., Christy R. Optical constants of transition metals: Ti, V, Cr, Mn, Fe, Co, Ni, and Pd. *Physical Review B*. 1974; 9: 5056–5070. <https://doi.org/10.1103/PhysRevB.9.5056>
 35. Ahmad J., Alhadlaq H.A., Siddiqui M.A., Saquib Q., Al-Khedhairi A.A., Musarrat J., Ahamed M. Concentration-dependent Induction of reactive oxygen species, cell cycle arrest and apoptosis in human liver cells after nickel nanoparticles exposure. *Environmental Toxicology*. 2015; 30(2): 137–148. <https://doi.org/10.1002/tox.21879>
 36. Deng Q., Wan Q., Liao J., Fang D., Wang L., Xiong S., Xu P., Shen X., Li Q., Zhou Y. Nickel nanoparticles affect the migration and invasion of HTR-8/SVneo cells by downregulating MMP2 through the PI3K/AKT pathway. *Toxicology in Vitro*. 2022; 80: 105328. <https://doi.org/10.1016/j.tiv.2022.105328>
 37. Journeay W.S., Goldman R.H. Occupational handling of nickel nanoparticles: A case report. *American Journal of Industrial Medicine*. 2014; 57(9): 1073–1076. <https://doi.org/10.1002/ajim.22344>
 38. Åkerlund E., Cappellini F., Di Buccianico S., Islam S., Skoglund S., Derr R., Odnevall Wallinder I., Hendriks G., Karlsson H.L. Genotoxic and mutagenic properties of Ni and NiO nanoparticles investigated by comet assay, γ -H2AX staining, Hprt mutation assay and Tox-Tracker reporter cell lines. *Environmental and Molecular Mutagenesis*. 2018; 59(3): 211–222. <https://doi.org/10.1002/em.22163>
 39. Magaye R.R., Yue X., Zou B., Shi H., Yu H., Liu K., Lin X., Xu J., Yang C., Wu A., Zhao J. Acute toxicity of nickel nanoparticles in rats after intravenous injection. *International Journal of Nanomedicine*. 2014; 2014(9): 1393–1402. <https://doi.org/10.2147/IJN.S56212>