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Magnetic Nanodiscs for Malignant Neoplasms Treatment

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ABSTRACT

The steady increase in cancer incidence, leading to high mortality and disability rates among the working-age population, underscores the importance of developing innovative therapeutic approaches. One promising strategy is magnetically guided microsurgery of individual tumor cells using functionalized magnetic nanostructures. Among different types of magnetic particles, nanodiscs demonstrate the greatest potential owing to their unique magnetic properties. Their capacity for modification with targeting molecules allows the development of highly specific systems for selective action on tumor cells. This review assesses the prospects of applying functionalized magnetic nanodiscs (referred to as a *smart nanoscalpel*) for the selective destruction of malignant cells. Materials and methods included a systematic analysis of scientific publications from 2022 to 2025 in *PubMed* using the keywords *magnetic nanodiscs*, *malignant neoplasms*, and *magnetic nanoparticles*. Particular attention is given to the mechanisms by which nanodiscs, under the influence of an alternating magnetic field, can selectively destroy tumor cells whereas preserving the viability of surrounding healthy cells. The analysis highlights the considerable potential of targeted magnetic nanodiscs as a promising adjuvant tool for the selective elimination of residual tumor cells in the postoperative period, as well as for the treatment of disseminated metastatic foci. However, translation of the magnetomechanical approach from experimental research into clinical practice requires comprehensive preclinical studies, including optimization of the physicochemical parameters of nanodiscs, thorough evaluation of efficacy and safety, and the development of standardized application protocols.

Keywords: magnetic nanodiscs; neoplasms; malignant; magnetomechanical therapy; aptamers; alternating magnetic field.

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Магнитные нанодиски для терапии злокачественных новообразований

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АННОТАЦИЯ

Неуклонный рост онкологической заболеваемости, приводящий к значительным показателям смертности и инвалидизации среди трудоспособного населения, обуславливает актуальность разработки инновационных методов терапии. Особый интерес исследователей вызывает перспективное направление магнитоуправляемой микрохирургии отдельных опухолевых клеток, основанное на применении функционализированных магнитных наноструктур. Среди различных типов магнитных частиц наибольший потенциал демонстрируют нанодиски, обладающие уникальными магнитными характеристиками. Возможность их модификации таргетными молекулами позволяет создавать высокоспецифичные системы для направленного воздействия на опухолевые клетки. В данном обзоре проведена оценка перспектив применения функционализированных магнитных нанодисков («умный наноскальпель») для селективного уничтожения злокачественных клеток. Материалы и методы исследования включали систематический анализ научных публикаций за 2022–2025 гг. в базе данных PubMed по ключевым словам «magnetic nanodiscs», «malignant neoplasms», «magnetic nanoparticles». Особое внимание уделено изучению принципов работы нанодисков, способных под воздействием переменного магнитного поля избирательно разрушать опухолевые клетки при сохранении жизнеспособности окружающих здоровых клеток. Проведённый анализ демонстрирует большой потенциал таргетных магнитных нанодисков в качестве перспективного адъювантного инструмента для селективной элиминации остаточных опухолевых клеток в послеоперационном периоде, а также для терапии диссеминированных метастатических очагов. Однако трансляция магнитомеханического подхода из экспериментальных исследований в клиническую практику требует проведения комплексных доклинических испытаний, включающих оптимизацию физико-химических параметров нанодисков, тщательную оценку эффективности и безопасности и разработку стандартизированных протоколов применения.

Ключевые слова: магнитные нанодиски; злокачественные новообразования; магнитомеханическая терапия; аптамеры; переменное магнитное поле.

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INTRODUCTION

In recent years, there has been a global increase in the incidence of cancer, which results in high mortality and disability among the working-age population [1–3]. The primary treatment modalities for patients with malignant neoplasms are surgery, radiation therapy, and chemotherapy. However, each of these modalities has limitations that reduce the effectiveness of antitumor therapy. In particular, surgical intervention does not guarantee the complete removal of tumor cells from tissues adjacent to the tumor lesion, which may provoke disease recurrence. Therefore, the development of novel, unconventional approaches to the treatment of oncological diseases remains relevant.

One of the approaches is magnetomechanical therapy, in which tumor cells are destroyed under the influence of an alternating magnetic field using magnetic nanoparticles with targeted activity. It is important to emphasize that an alternating magnetic field is virtually harmless to the human body: it penetrates tissues to any depth without attenuation, whereas simultaneously altering the physical properties of magnetic nanoparticles. The use of magnetic fields for remote control of magnetic nanoparticles within the body and the possibility of their visualization by magnetic resonance imaging (MRI) and computed tomography (CT) form the basis for therapeutic and diagnostic interventions in theranostics. Therefore, the most suitable targeted agents from a surgical standpoint are magnetic nanoparticles capable of transforming magnetic moments into mechanical action.

The use of biologically functional molecules that can recognize and interact with pathological targets further enhances magnetomechanical therapy technologies.

Physico-technical and engineering solutions based on nuclear and quantum physics, magnetism, optics, nonlinear optics, spectroscopy, electronics, and information technologies have long been applied in medical device development. For a long time, medical electronics were directed mainly toward the diagnosis of pathological changes and treatment monitoring, whereas the therapeutic application of electromagnetic fields was confined primarily to physiotherapy for tumors and edema. Technological advances in this field, combined with agents containing magnetic nanoparticles, have shown that nanomedicine can also employ remotely controlled medical devices for therapeutic and diagnostic interventions at the molecular and cellular levels, as well as personalized and noninvasive theranostic technologies for many diseases.

AIM

This study aimed to evaluate the potential of functionalized magnetic nanodiscs (nanoscalpel), conjugated with tumor-recognizing molecules, for microsurgery of individual tumor cells.

SEARCH METHODOLOGY

Materials and methods included a systematic analysis of scientific publications in the PubMed database using the keywords magnetic nanodiscs, magnetic nanoparticles, and malignant neoplasms for the period from October 2022 to February 2025. The search depth was 24 years. A PubMed search for magnetic nanodiscs identified 30 articles; after excluding non–full-text papers and duplicates, 18 publications were included in this review. A search for magnetic nanoparticles identified 40 articles, of which 22 were included after exclusions. A search for malignant neoplasms yielded 15 articles, 5 of which were included in this review after exclusions.

DISCUSSION

Magnetomechanical Therapy of Malignant Cells

Magnetomechanical therapy of malignant tumors using magnetic nanoparticles delivered into the tumor and exposed to a low-frequency alternating magnetic field is an emerging field of nanomedicine and has considerable potential for the treatment of oncological diseases. The principle of magnetomechanical therapy is to apply mechanical force to tumor cells in order to destroy them. Magnetic nanoparticles, when subjected to a low-frequency, low-intensity alternating magnetic field, generate mechanical force and stress within surrounding cells by transforming magnetic moments into mechanical action. The mechanical forces generated by magnetic nanoparticles may disrupt the cell membrane in some cases and intracellular structures in others, ultimately leading to tumor cell death. To enhance therapeutic efficacy and minimize adverse effects, magnetic nanoparticles functioning as a nanoscalpel are functionalized with targeting molecules (antibodies, peptides, aptamers) to enable specific binding to target cells.

The most widely discussed option in the scientific data for a remotely controlled magnetic tool designed to destroy tumor cells is the magnetic nanoparticle coated with a biologically inert gold shell. In a low-frequency magnetic field, its mechanical oscillations can induce necrosis or apoptosis of the target cell,

whereas in a high-frequency field, plasmonic or ferromagnetic resonance can be induced, leading to nanoparticle heating and hyperthermia of the target tumor cell [4, 5]. Targeting elements most often include monoclonal antibodies, aptamers, and peptides, which provide selective interaction and strong physicochemical binding to various target cell proteins. In addition, the biomedical performance of the nano-instrument can be enhanced through functionalization with optical, fluorescent, or radiological probes, as well as chemotherapeutic or radiopharmaceutical agents.

Various physical forces can be employed for the destruction of tumor cells, including ionizing radiation [4], as well as mechanical or thermal energy [4, 5]. This imposes certain requirements on magnetic nanoparticles. In particular, their ability to transform one type of energy into another. The most suitable structures for converting magnetic field energy into mechanical energy are magnetic micro- and nanostructures, which can be manipulated—directed, concentrated, rotated, or vibrated.

The most promising source for generating thermal or mechanical energy is the magnetic field, which offers several undeniable advantages, biosafety foremost among them. The most promising converters of magnetic field energy are magnetic particles capable of transforming the field energy into thermal or mechanical energy [6–8]. Importantly, this conversion of magnetic field energy into thermal or mechanical energy can occur in any part of the body containing magnetic nanoparticles, since magnetic fields penetrate tissues to any depth without restriction. Accordingly, remotely controlled magnetic nanoparticles can induce tissue hyperthermia, leading to thermal damage of tumor cells, or mechanical oscillations of the particles, inducing mechanical damage to tumor cells [6–8]. Depending on the site of action, the mechanical force generated by magnetic nanoparticles may disrupt the cell membrane [6, 9] or intracellular structures [6, 10–13].

Thus, the magnetic moment of nanoparticles generated by a magnetic field, due to their magnetic anisotropy, is converted into a torque acting on the physical particle, which induces magnetomechanical or thermal destruction of tumor cells. For microsurgical applications in malignant tumors, magnetomechanical destruction of tumor cells is considered the most attractive approach.

Magnetomechanical transduction can act on death receptors [14], ion channels [4], or directly damage the cell [9–11]. This effect has been demonstrated not only *in vitro* [4, 9] but also *in vivo* [6, 14].

Magnetic Nanoparticles as Tools for Theranostics of Malignant Neoplasms

Optimizing magnetic nanoparticles for anticancer therapy presents a complex research challenge, given the wide variety of such particles potentially suitable for destroying malignant cells. Magnetic nanoparticles differ in size and structure; they can be heterogeneous or homogeneous and also vary in their magnetic properties, which are determined by both chemical composition and the type of interaction with neighboring particles [15]. Recently, superparamagnetic nanoparticles—particles exhibiting the property of superparamagnetism—have gained particular attention. These particles display magnetic behavior only in the presence of an external magnetic field. Superparamagnetic nanoparticles do not retain magnetization in the absence of a magnetic field, which allows for their remote manipulation and control of their movement [16].

In biomedical research, such particles have been successfully applied in MRI and for the induction of hyperthermia. However, their effectiveness in magnetomechanical destruction of tumor cells has reached its limit [16], since their magnetic response is constrained by particle size, above which aggregation occurs [17]. At the same time, anticancer efficacy increases with the magnitude of the magnetic moment and, therefore, with particle size. Thus, for magnetomechanical therapy, magnetic nanoparticles must exhibit a sufficiently high magnetic moment without aggregation [18].

In a three-layer nanodisc composed of “nonmagnetic material–magnetic material–nonmagnetic material,” interfacial forces can arise that significantly affect both the magnitude and orientation of the resulting magnetization. Theoretically, it has been demonstrated that magnetostrictive forces at the material interfaces, shape anisotropy at the disc edges, and spin–spin exchange interactions, under certain material characteristics and disc dimensions, must be taken into account, as this enables the design of heterogeneous nanostructures suitable for use as a nanoscalpel in a low-frequency magnetic field. Furthermore, the chemical synthesis of superparamagnetic particles remains highly challenging for large-scale production due to relatively low yield and poor reproducibility of nanoparticle quality [19].

Another limitation in the widespread use of superparamagnetic nanoparticles for microsurgery of malignant tumors is the difficulty of their synthesis [19]. Analysis of the full spectrum of magnetic nanostructures for application in magnetomechanical tumor cell destruction has shown that the most suitable candidates are magnetic discs, which combine high saturation magnetization

with the absence of remanent magnetization [20]. The magnetic properties of discs help prevent agglomeration and facilitate remote control of these structures. Thus, magnetic discs have emerged as the most appropriate magnetomechanical tools for the destruction of tumor cells.

Several types of magnetic discs have been described in the scientific data, including synthetic antiferromagnetic discs [21], vortex discs [9], and discs with pronounced magnetostrictive properties and low anisotropy [22, 23].

Antiferromagnetic discs consist of two ferromagnetic layers separated by a nonmagnetic one. The magnetic moments of the ferromagnetic layers are oppositely directed and compensate each other, but under an external magnetic field they align in the same direction [24–26]. By varying the thickness of the magnetic layers, it is possible to control the dispersion of discs in buffer solutions [26, 27]. In vortex discs, the magnetic moments curl in-plane, taking the form of closed loops. At the center of the disc, in the vortex core, the magnetic moments are oriented perpendicular to the plane. These discs, like synthetic antiferromagnetic discs, exhibit zero net magnetization. Exposure to an external magnetic field causes a displacement of the vortex core. When the vortex reaches the disc edge, the disc becomes magnetically saturated [9]. By adjusting the size and shape of vortex discs, the vortex configuration can be optimized [28] to achieve the desired level of magnetic susceptibility under conditions of absent disc agglomeration [21, 29, 30], which is critical for enabling magnetomechanical destruction of tumor cells.

In the study by Orlov et al. [18], physical–mathematical models theoretically demonstrated the potential of thin-film nickel nanodiscs with gold bilayer coatings as nanoscalpels for noninvasive cellular surgery of tumors. It was shown that the difference in thermal expansion coefficients between the ferromagnetic and nonmagnetic materials, along with the associated magnetoelastic effects, makes a substantial contribution to the effective magnetic anisotropy of a three-layer nanodisc, in which the ferromagnetic layer thickness is smaller than its diameter (by tens to hundreds of times). In the case of an Au/Ni/Au trilayer nanodisc, the contribution of magnetoelastic effects to anisotropy is comparable to that of crystallographic anisotropy and shape anisotropy.

The results of studies on the magnetic properties of three-layer magnetic nanodiscs demonstrated that they exhibit a high level of saturation magnetization with virtually no remanent magnetization, which prevents their agglomeration

[31]. Under low-frequency alternating magnetic fields, magnetic nanodiscs conjugated with targeting molecules (DNA aptamers) transformed magnetic moments into mechanical oscillations that mechanically destroyed Ehrlich ascites carcinoma cells both *in vitro* and *in vivo* [31].

Scientific and technical aspects of developing a three-layer Au/Ni/Au nanodisc functionalized with DNA aptamers, as well as biomedical technologies for its application in targeted microsurgery of glioblastoma, were also discussed in the study by Fedotovskaya et al. [23]. It was shown that magnetic nanodiscs functionalized with targeting molecules (“smart nanoscalpel”) can be remotely controlled by a low-frequency magnetic field and, at the molecular and cellular levels, selectively recognize and destroy human glioblastoma cells *in vitro* and *in vivo* without damaging normal cells of the surrounding healthy tissues.

Magnetic discs for magnetomechanical destruction of tumor cells are fabricated using lithography and physical deposition. These methods enable control over the size, composition, and shape of the discs, making the manufacturing process automated and reproducible [21, 31, 32]. Modifications of these technologies allow for reducing the disc size to as small as 30 nm, if necessary [33].

Au/Ni/Au magnetic nanodiscs with a size of 600 nm, which demonstrated high antitumor efficacy against Ehrlich ascites carcinoma cells and human glioblastoma cells *in vitro* and *in vivo* [23, 31, 34], were produced by optical lithography and electron-beam evaporation.

Magnetic Discs for Microsurgery

The ability to perceive mechanical stimuli (mechanosensitivity) is a universal property of living systems, underlying both exo- and endoreceptor mechanisms that regulate parameters of the internal and external environment. Through mechanoreceptors, regulation of cellular functional status, tissue growth processes, stem cell differentiation [35, 36], as well as control of cell death (apoptosis and necrosis), is carried out. Thus, mechanosensitivity, which is also inherent to tumor cells, opens up opportunities for targeted modulation of their functional activity.

Magnetic discs with vortex, antiferromagnetic, and planar quasi-dipolar structures possess a unique capacity to transform the energy of low-frequency rotating or alternating magnetic fields into mechanical effects. This property opens up new possibilities for developing methods of remotely controlling the functional state of cells, including promising approaches to controlled microsurgery at the cellular level.

The considerable research interest in magnetic discs is driven by their high efficiency in destroying tumor cells. The unique magnetic sensitivity of these structures is explained by their ability to acquire pronounced magnetization under weak external fields, despite having zero net magnetization in the absence of a field [9, 37]. Pioneering studies by Kim et al. demonstrated that vortex discs exposed to a rotating field induced death in 90% of glioblastoma cells *in vitro* [9]. Subsequent studies confirmed the cytotoxic effects of vortex microdiscs against tumor cells both *in vitro* and *in vivo* [4, 6, 11, 21]. Importantly, nanodiscs with a diameter of 140 nm exhibit stronger antitumor activity than microdiscs (1 μm).

Not only vortex discs but also synthetic antiferromagnetic discs (SAF and P-SAF) are capable of inducing tumor cell death under magnetic field exposure. In a comparative analysis of cytotoxic activity, Mansell et al. found [38] that P-SAF discs were five times more effective than vortex discs in destroying tumor cells.

The authors' calculations showed that, under a rotating field, a microdisc with uniaxial anisotropy provides continuous torque application, rather than a transient effect observed only at the moment of field introduction, as in the case of a microdisc with an easy-plane of magnetization.

Analysis of the frequency dependence of the cytotoxic action of magnetic discs revealed maximum efficiency in the range of 10–20 Hz, resulting in the death of ~90% of cells. When the frequency increased to 40 Hz, the cytotoxic effect decreased to ~75%, whereas at 50 Hz only ~25% of cells were killed. Complete absence of cytotoxic activity was observed at 60 Hz [9]. Wong et al. [30] investigated the effects of the low-frequency range (1–20 Hz) and found a moderate enhancement of the effect with decreasing frequency: cell viability decreased from ~80% at 10 Hz to ~73% at 1 Hz.

There are significant differences in the biological effects of magnetic discs *in vitro* and *in vivo*, owing to the complexity of the multicomponent circulatory system compared with cell culture conditions. To ensure effective therapeutic action, it is necessary to consider disc behavior not only at the cellular level but also within the changes of the bloodstream and tumor tissue. According to the analysis by Wilhelm et al. [39], only about 1% of nanoparticles introduced into the body reach solid tumor cells, whereas most accumulate in the reticuloendothelial system (liver, spleen, lungs) [39, 40]. Small nanoparticles are eliminated mainly through the kidneys, lymphatic system, and skin. The biocompatibility and tumor specificity of magnetic particles can be enhanced by

functionalization with targeting ligands, particularly aptamers [41].

Magnetic nanodiscs functionalized with DNA aptamers targeting specific cellular proteins can exert significant mechanical effects on the membrane of a target cell under alternating or rotating magnetic fields, ultimately leading to its disruption.

Anisotropic magnetic discs, when moving through the bloodstream under the influence of inertial and hydrodynamic forces, tend to shift toward the vascular wall and subsequently drift laterally along flow lines toward the endothelium [42]. This behavior is highly likely to result in their adhesion to endothelial cells in the vicinity of the tumor site, thereby facilitating extravasation into tumor tissue through the mechanism of enhanced permeability and retention (EPR effect). Anisotropic magnetic particles demonstrate increased efficiency of penetration into tumor tissue [43]. This is associated with their ability to generate oscillatory motions under hydrodynamic or magnetic forces, which enhances their interactions with the vascular wall and facilitates subsequent transmigration into the tumor lesion [21, 44].

A schematic illustration of these properties, relevant to biomedical applications, is shown in Fig. 1.

Tumor tissue is characterized by heterogeneous vascularization: the highest vessel density is observed at the tumor–normal tissue interface, whereas central regions often exhibit reduced blood supply with areas of necrosis [45]. Increased blood viscosity caused by plasma proteins slows blood flow in tumor vessels, thereby promoting nanoparticle retention and creating favorable conditions for their extravasation into the tumor matrix. A critical parameter of magnetic particles is their size—it must allow free passage through microcapillaries without the risk of embolization and facilitate effective diffusion into the tissue [45].

Binding of Magnetic Nanodiscs with Tumor-Cell Recognizing Molecules

Although magnetic discs used in magnetomechanical therapy exhibit zero magnetization in the absence of an external field, aggregation of these structures can still occur. This is due to their high anisotropy, which promotes hydrophobic interactions strengthened by van der Waals attraction forces [21]. To reduce clustering of magnetic discs and improve their stability, surface modification is applied using surfactants, dyes, polymers, or natural dispersants such as silica or gold. However, this approach has drawbacks, as coating the discs with nonmagnetic materials reduces their saturation magnetization [21].

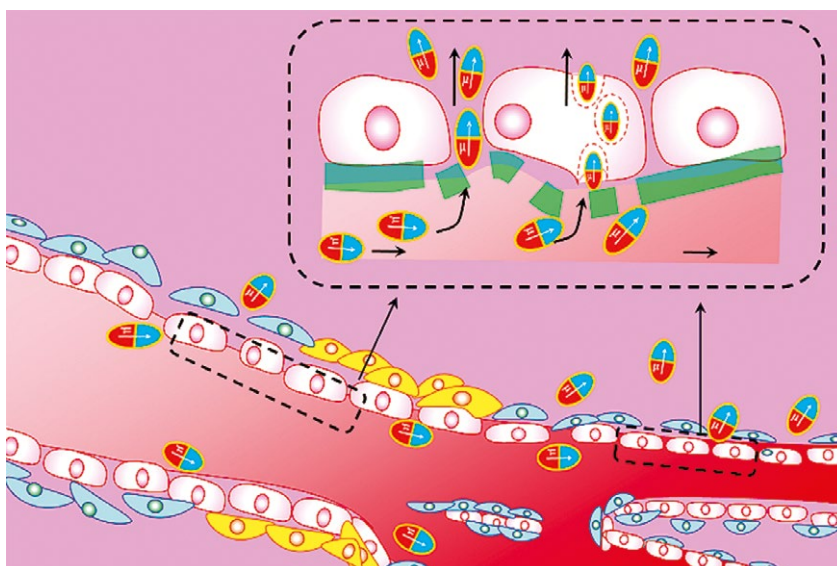


Fig. 1. The shape of nanodiscs (large area with small thickness) facilitates their movement along the walls of blood vessels, and in tumors where there are disturbances in the basal vascular membrane, nanoparticles penetrate it more easily.

Functionalization of magnetic discs significantly enhances their stability and ensures targeted action on tumor cells as pathological targets. Minimizing side effects critically depends on achieving selective accumulation of particles exclusively within tumor cells, which is accomplished through functionalization with specific ligands. Furthermore, the *in vivo* biodistribution efficiency of magnetic discs depends on several factors, including local blood flow characteristics, pH level, vascularization features, and the organization of the extracellular matrix.

To enhance the efficiency of magnetic disc transport into tumor tissue, specific targeting using ligands complementary to biological targets is required. Such targets may include peritumoral and intratumoral vessels, components of the extracellular matrix, surface antigens of tumor cells, or intracellular targets. Unlike passive targeting, in which particles are coated only with stabilizing agents, functionalization of magnetic carriers with affinity ligands substantially increases their specific accumulation in tumor tissue.

Aptamers are an optimal choice for functionalizing magnetic particles due to a number of unique properties:

- versatility of selection toward various molecular targets;
- high specificity and binding affinity;
- scalability of chemical synthesis;
- no risk of biological contamination during production;
- low immunogenicity and absence of toxicity;
- small molecular size enabling effective penetration into tumor tissue;

- ability to undergo reversible folding while restoring native conformation and maintaining stability of the phosphodiester backbone;
- compatibility with chemical modification without disruption of spatial structure;
- ease of introducing fluorescent markers or functional groups at the synthesis stage.

Toxicity and Efficacy of Magnetic Discs

In the development of new therapeutic agents, special attention should be given to a comprehensive evaluation of the biocompatibility and toxicological profile of the applied materials, which is a prerequisite for ensuring both safety and clinical efficacy. In this regard, numerous *in vitro* and *in vivo* studies have been conducted to investigate the toxicological properties of magnetic nanodiscs [4, 22, 37]. The findings indicate that in the absence of exposure to an alternating magnetic field, magnetic nanodiscs exhibit no cytotoxic activity and have no effect on the viability of either tumor or normal cells, regardless of the concentration used.

The efficacy of magnetomechanical therapy can be very high, reaching up to 100% both *in vitro* and *in vivo*. Overall, its efficacy is determined by a combination of factors—such as the shape, size, and magnetic properties of the discs, the parameters of the magnetic field, and the presence of targeting molecules on the disc surface, etc. [4–16].

The evaluation of magnetic nanodiscs for magnetomechanical microsurgery of malignant tumors in experimental animals with pharmacologically suppressed immunity and orthotopically transplanted human glioblastoma biomaterials is described in

the study by Fedotovskaya et al. [23]. A schematic illustration of glioblastoma magnetomechanical therapy is shown in Fig. 2.

CONCLUSION

The key objective in the treatment of malignant neoplasms is the elimination of all tumor cells, including dormant ones, to prevent recurrence. For this reason, surgical intervention remains one of the most frequently used therapeutic modality in oncology. However, its invasive nature represents a limitation. Moreover, surgery does not guarantee the complete removal of all tumor cells, which can result in metastasis and the development of secondary tumor lesions.

In recent years, a new strategic approach has been developed to overcome the limitations of surgical cancer therapy—one that enables the elimination of individual tumor cells invisible to the surgeon's eye without damaging healthy cells. The essence of this promising approach lies in the use of nanostructures with unique magnetic properties, which specifically bind to individual tumor cells and act as a nanoscalpel. Under the influence of an alternating magnetic field, magnetic nanostructures convert magnetic moments into mechanical action, which, depending on the intensity, frequency, and waveform of the magnetic field, induces either necrosis or apoptosis of the tumor cell without damaging adjacent healthy cells. An undeniable advantage of this approach is that such magnetic nanostructures can be remotely controlled

by a biocompatible magnetic field that penetrates deeply into tissues.

Analysis of the scientific data indicates that the most promising magnetic nanostructures are magnetic nanodiscs, as they exhibit zero magnetization in the absence of a magnetic field, which prevents agglomeration, and under the influence of an external magnetic field they convert magnetic moments into mechanical torque. Their specificity is provided by tumor-recognizing molecular elements, including antibodies and aptamers. Another advantage of magnetic nanodiscs is their anisotropic shape, which promotes movement along the periphery of blood vessels, thereby increasing the probability of their passage into the tumor through the endothelium.

The key directions for advancing magnetomechanical therapy using magnetic nanodiscs include improving their design (optimizing magnetic parameters, enhancing biocompatibility, and targeted delivery) and studying the fundamental mechanisms of their action (the molecular basis of magnetomechanical effects, precise mechanisms of induced tumor cell death, and factors determining the pathways of programmed cell death).

Thus, the analysis of the scientific data suggests that targeted magnetic nanodiscs may become a promising adjunct tool for eliminating both residual tumor cells after primary surgery and distant metastases; however, the transition of magnetomechanical therapy from research to clinical trials requires thorough testing and optimization.

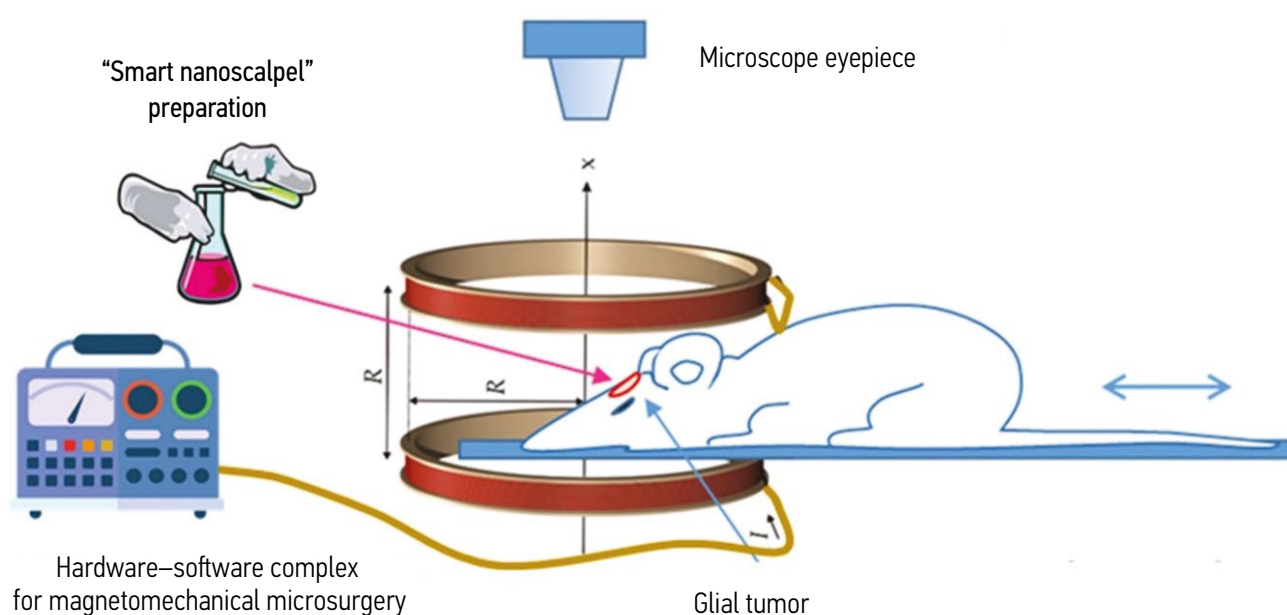


Fig. 2. Microsurgery of glial brain tumor using magnetic nanodiscs remotely controlled by a magnetic field.

ADDITIONAL INFORMATION

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