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MINI-REVIEW

Nanopowder Boron Compounds Doped with Ferromagnetic Clusters for BNCT

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Abstract

Study examines the problem of development of novel nanomaterials serving for boron ^{10}B isotope delivery agents in Boron-Neutron-Capture-Therapy (BNCT). For this purpose, there is done a mini-review on nanopowder boron compounds especially prospective for BNCT; magnetic nanocarriers of the therapeutically active agents in general, delivery of which can be controlled by using of an external magnetic field; as well as methods of synthesis of nanocomposites comprising components of both kinds. Based on recent literature analysis, boron nitride and boron carbide nanopowders doped with ferromagnetic iron oxide nanoclusters are recommended for BNCT as effective delivery agents with good biocompatibility.

Key Words: *Nanopowder; Ferromagnetic cluster; Boron compound; Boron-neutron-capture-therapy; Drug delivery agent*

Introduction

Boron compounds are of great interest for the Boron-Neutron-Capture-Therapy (BNCT), which from last decade has been actively utilized for treatment of several aggressive cancers, including locally invasive very malignant tumors such as melanoma, gliomas (cerebral glioblastoma multiform), recurrent head and neck, and triple negative breast cancers, where standard chemo- and radiation therapies reveal their shortcomings [1-4].

Figures 1 and 2 illustrate the principles of the BNCT. A collimated (epi)thermal neutrons beam must be absorbed by the tumor cells to sustain a lethal ^{10}B (n, α) ^{7}Li capture reaction. Since the α-particles have very short mean path-length in tissues (5–9 μm), their destructive effect is limited to boron-containing cells. BNCT might provide a selective destroying of tumor cells and spare of surrounding normal tissue if the required amounts of ^{10}B nuclei and neutrons are delivered.

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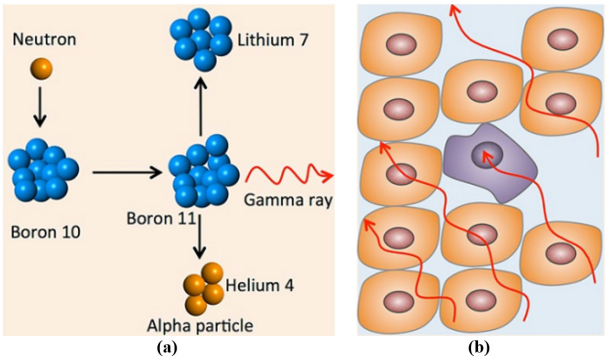

Figure 1) *(a) BNCT is based on nuclear capture and fission reactions that occurs when non-radioactive ^{10}B nucleus is irradiated with thermal or low-energy (~0.025 eV) and epithermal or moderate-energy (~10^3 eV) neutrons, which become thermalized as they penetrate tissues. Resulting ^{10}B (n, α) ^{7}Li capture reaction yields high Linear-Energy-Transfer (LET) α-particle (^{4}He) and ^{7}Li nucleus. (b) A sufficient amount of ^{10}B atoms (20-50 μg/g or ~10^9 atoms/cell) must be delivered selectively to the tumor in order to make BNCT successful. Figures 1(a) and 1(b) from [1] – used with permission under terms of Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.*

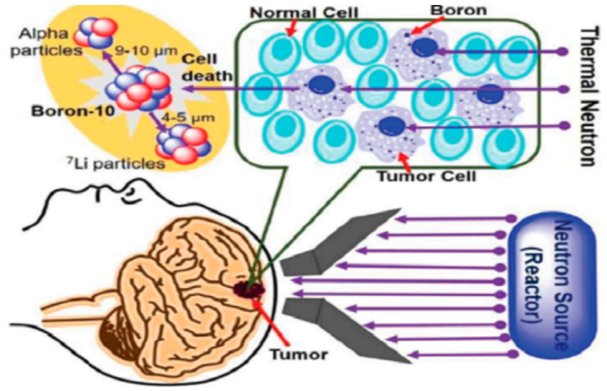

Figure 2) *Graphical depiction of the BNCT principle showing how localized boron-containing particles in the tumor can be bombarded with thermal neutrons to produce α-particles and Li-nuclei. If neutron capture is targeted to cancer cells, Li and He products kill these cells without damage to the healthy neighboring ones. Figure 2(a) from [2] – used with permission under terms of Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.*

BNCT is one of the most promising cancer radiation therapy methods, which can successfully combine highly effective combating the specific aggressive forms of cancer with practically total prevention of radiation-induced damages to healthy tissues. As for its actuality, it is directly related to the rapid growth in the BNCT relevance today, when, on the one hand, there are available portable neutron sources suitable for this therapy and, on the other hand, effective boron ^{10}B isotope delivery agents in the form of nanosystems with high content of boron.

In current clinical practice, the delivery of neutron-absorbing centers – boron ^{10}B isotopes – to tumor cells usually is done by the use of boron-containing organic macromolecules, which are characterized by a predominant accumulation in the tumor. The disadvantage of this approach is the insufficient content of boron in macromolecular carriers and, consequently, in the target tumor tissues as well. Two types of boron-containing drugs with moderate selectivity have been utilized for treatment most of patients using BNCT: sodium borocaptate (BSH) and boron phenylalanine (BPA). Their replacing by new tumor-targeted boron compounds having heightened *in vivo* and/or *in vitro* efficacies is required to realize the full clinical potential of the BNCT. Any boron-containing agent to be useful for BNCT should fulfill the following requirements:

- Low toxicity
- Critical concentration in tumor (at least ~30 μg^{10}B/g)
- High tumor- and low normal-tissues uptake; and
- Rapid normal-tissue clearance in combination with the persistence in tumor-tissue during the treatment procedure.

Many molecule-based boron carriers (porphyrins, amino acids, polyamines, nucleosides, peptides, monoclonal antibodies, liposomes, boron cluster compounds and co-polymers, etc.) have been explored. However, they show insufficient accumulation of boron in tumor cells. There are attempts to overcome this problem by developing boron-containing nanosystems (for delivering at least 20 ppm

of B to the tumor cells): boron nitride BN nanotubes and nanoparticles, boron-containing gold Au nanoclusters and nanoparticles, boron-based amino acids and polymers, etc. From the recent literature analysis our choice is made for boron nitride BN and boron carbide B_4C based nanocarriers [5] for their:

- High boron content;
- Good tumor-to-nontumor boron accumulation ratio;
- Good biocompatibility;
- Low toxicity and almost negligible other side-effects related to their high chemical and oxidative stabilities;
- Possibility to overcome mechanism of cancer multidrug resistance due to tumor progression; and
- Possibility to undergo rapid on-demand degradation under physiological conditions.

The novelty of our approach lies in the basic idea of responding to the above challenge of medical physics by creating ferromagnetic nanopowders with high boron content that can be transported to tumor cells with exposure to an external magnetic field. Below, the proposed approach is argued by a mini-review of the recent literature available on the boron ^{10}B isotope carriers, accumulation of therapeutically active agents in the target tissues under the magnetic field influence, as well as possibilities to develop methods for the synthesis of the boron compounds nanopowder doped with ferromagnetic nanoclusters.

The paper is structured in following way. Just after the present Introduction giving a brief overview on BNCT we answer the question why boron nitride and boron carbide nanopowders can serve as effective and safe delivery agents for boron ^{10}B isotopes in neutron therapy of cancer. Next section describes available magnetic nanocarriers allowing controlled delivery of therapeutically active agents in general. Following section merges these two issues together by providing possible synthesis routes for ferromagnetic clusters doped boron nitride and boron carbide nanopowders. And finally, there are formulated Conclusions of the conducted literature analysis.

Boron Nitride and Boron Carbide as Boron ^{10}B Isotope Delivery Agents

There are available a few reports on the use of boron nitride nanotubes and nanoparticles for boron carriers in BNCT. To enhance the selective targeting and ablative efficacy of BNCT for tumors, for the first time, boron nitride nanotubes as carriers of boron atoms were used in [6]. Following their dispersion in aqueous solution by noncovalent coating with biocompatible poly-L-lysine (PLL) solutions, BN nanotubes were functionalized with a fluorescent probe in form of quantum dots to enable their tracking and folic (F) acid as selective tumor targeting ligand. *In vitro* studies confirmed substantive and selective uptake of these nanovectors (Figure 3) by glioblastoma multiform cells.

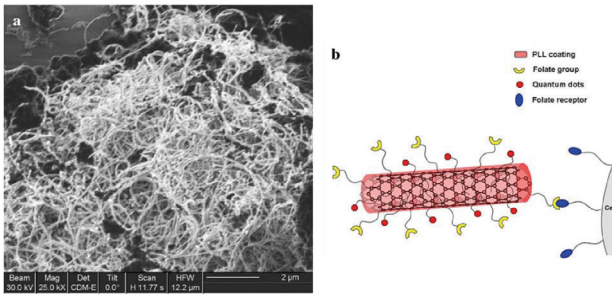

Figure 3) *(a) Focused-Ion-Beam (FIB) image of well-dispersed F–PLL–BNNTs. (b) Diagram of the proposed nanovector. Figures 1(a) and 1(b) from [6] – used with permission from co-author Dr. Vittoria Raffa.*

Boron nitride nanotubes also were functionalized [7] under mild conditions using a difunctional amine (such as glycine) with targeting ligand folic acid, an antibody against nerve growth factor. The BN nanotubes were loaded with a fluorescent probe for convenient imaging

of the treated glioblastoma multiforme cells. They demonstrated an increased efficiency of internalization within the glioblastoma multiforme cells compared to non-modified ones.

Creation of BN-based drug delivery nanocarriers with high chemical and, in particular, oxidative stability is one of the perspective ways to overcome the mechanisms of multidrug resistance of cancer. Using Chemical-Vapor-Deposition (CVD) the spherical boron nitride particles, 100–150 nm in diameter, with smooth or peculiar petal-like surfaces (Figure 4) were fabricated [8]. Then they were loaded with Doxorubicin (DOX). Drug loading efficacy was about 0.095 mg/mg. BN–DOX nanoparticles were relatively stable at neutral pH, whereas DOX was effectively released from them at acidic pH. Using confocal microscopy, the uptake of BN–DOX nanoparticles by various cells, including multidrug resistant ones, was studied. After intracellular delivery, most of them were found to be located in the endosomes/lysosomes.

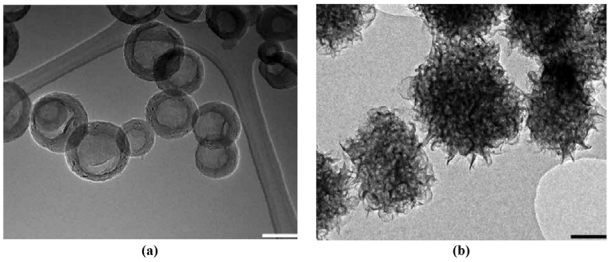

Figure 4) *Types of boron nitride nanoparticles (scale: 100 nm) with (a) smooth and (b) developed surfaces. Figures 1(a) and 1(b) from [8] – used with permission under terms of Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.*

Compared with photon-induced photo thermal and photodynamic cancer therapies, BNCT emerges as an alternative noninvasive treatment strategy that overcomes the problem of shallow penetration of light. But a key factor in performing the successful BNCT – to accumulate a sufficient amount of ^{10}B (>20 ppm) within tumor cells – remains a challenge for molecule-based boron drugs. In this regard, the Boron-Nitride-Nanoparticles (BNNPs) are promising due to their high boron content and good biocompatibility as they can undergo rapid degradation under physiological conditions. To design an on-demand degradable boron carrier, BNNPs were coated [9] by a Phase-Transitioned Lysozyme (PTL) that protects them from hydrolysis during blood circulation and can be readily removed by vitamin C after BNCT (Figure 5). The coated BNNPs exhibited high tumor B-accumulation, while maintaining a good tumor-to-nontumor ratio. Compared with the control group, animals treated with BNCT showed suppression of tumor growth, while almost negligible side effects were observed. Thus, the proposed strategy performed an on-demand degradation of BNNPs to avoid the toxicity caused by the long-term accumulation of nanoparticles.

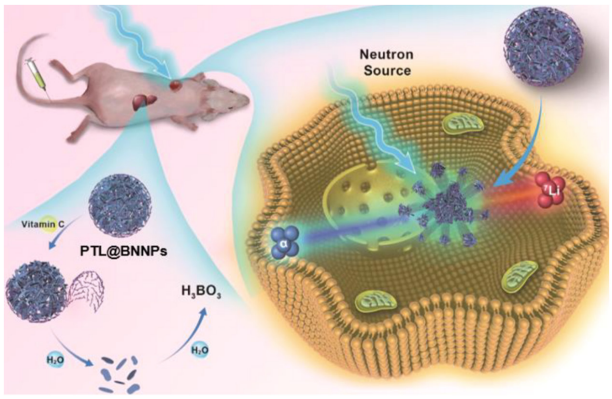

Figure 5) *Schematic illustration of PTL@BNNPs based BNCT and their on-demand degradation. Sch. 1 from [9] – reprinted with permission from authors.*

It should be mentioned that hexagonal boron nitride h-BN nanosheets and nanotubes possess properties, which enable them to be promising in the manipulations, including their functionalization with various organic molecules and biospecies [10], some of biomolecules reveal affinity to and selectivity for h-BN [11], and solid-state thermal neutrons detector based on ^{10}B-enriched h-BN epitaxial layer demonstrates its high detection efficiency [12].

To the best of our knowledge, there is available only a single report [13] on use boron carbide

nanoparticles for boron carriers in BNCT. To investigate the feasibility of the application of boron carbide nanoparticles as boron carriers in BNCT, the interaction between boron-rich boron carbide nanoparticles and selected tumor and immune phagocytic cells was studied experimentally. Boron carbide powder was prepared by the direct reaction between boron and soot using the transport of reagents through the gas phase. The obtained powder was ground and a population of nanoparticles with an average particle size about 80 nm was selected by centrifugation. The aqueous suspension of the nanoparticles was functionalized with human immunoglobulins (IgG) with or without labeling. It was shown that B_4C–IgG nanoconjugates may bind to phagocytic cells to be internalized by them (at least partially), whereas such nanoconjugates can only slightly interact with molecules on the cancer cells' surface.

Magnetic Nanocarriers for Controlled Delivery of Therapeutically Active Agents

In view of using ferromagnetic clusters doped boron nitride and boron carbide nanopowders in BNCT for boron-containing agents deliverable under the external magnetic field control, consider drugs' magnetic nanocarriers in general. Magnetic NanoParticles (MNPs) are a class of nanomaterials that can be manipulated using magnetic field. They possess other attractive properties, which could be seen in a number of potential uses in biomedicine, in particular, cancer tissue-specific targeting [14]. Their interactions in biological media rely on their crystal structure, size, and shape.

MNPs commonly consist of two components: a magnetic material (iron, nickel, cobalt, their oxides, etc.) and a component having chemical functionality (biomolecules like peptides, aptamer, antibodies, as well as chemotherapeutical drugs, nucleic acids, radionuclides, etc.). MNPs have been noticed widely as drug carriers due to their controllability, small (biocompatible subcellular) size, and large surface-to-volume ratio and surface properties allowing them to absorb proteins or lead to drugs and be directed to the desired location via a magnetic field. In the magnetic drug delivery, blood acts as the main fluid: the drug-loaded MNPs are injected near the tumor, which due to the intense and concentrated magnetic field gradient absorb the drug. Their superparamagnetic property helps in easy separation from the mixture component in the presence of an external magnetic field.

Using of MNPs to treat/cure advanced or metastatic cancer has a potential with minimal side effects through nanotechnology. However, to make such drug delivery successful one has to take into account many outside factors (like pH, temperature, osmolality, etc.) affecting it. Today, a number of reviews on magnetic nanocarriers of therapeutically active agents are available.

The review [15] focuses on the influences introduced by physical-chemical conditions and synthesis parameters on size, shape, and organic/inorganic surface coatings of SuperParamagnetic-Iron-Oxide-Nanoparticles (SPIONs), which have been extensively used in cancer therapy/diagnosis via magnetic targeting due to their remarkable magnetic properties, chemical stability and biocompatibility. Another review [16] examines the trend of synthesis of magnetite (iron oxide Fe_3O_4) based nanomaterials and their application in nanomedicine for the drug delivery.

To evaluate the outlook on a translation of magnetite nanoparticles for medical applications, including the magnetically controlled delivery of magnetite nanoparticles for cancer therapy, previously published research, as well as preclinical studies, clinical trials, and patent literature were examined [17]. For such example, it was schematically represented the application

of MNPs for targeted blood vessel delivery of thrombolytic agents.

The review [18] is focused on nanosuspensions, nanofluids with solid particles, in particular, applying the magnetic nanofluid systems for targeted drug delivery. In view of magnetic nanoparticle materials great impact on nanomedicine an up-to-date overview of its history, concept and recent applications, in particular, for cancer treatment was done in [19]. Paper [20] reviews the synthesis methods of most important MNPs, their functionalization with different materials and related monitorization of the cancer cells. Figure 6 illustrates the magnetic drug targeting in the tumoral zone [20].

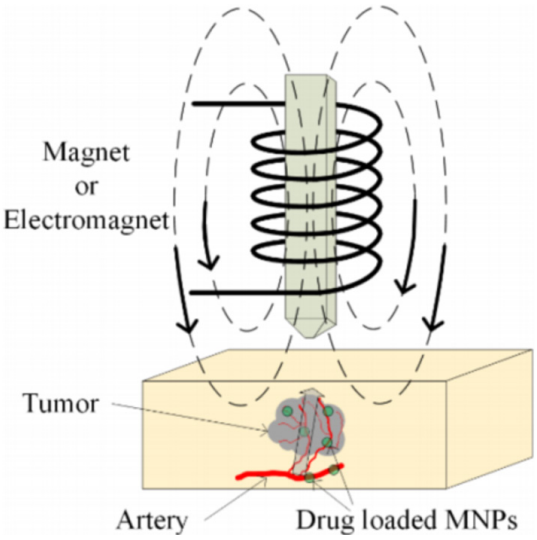

Figure 6) *Magnetic drug targeting application. Drug-loaded MNPs are directly injected in the arterial blood of the tumor. A magnetic field applied causes their enhancement in the tumoral zone. Figure 13 from [20] – used with permission under terms of Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.*

Despite other review reports on MNPs, the review [21] uncovers insights into their fabrication processes or surface functionalization for biomedical applications but discusses some special magnetic nanocomposites for smart drug delivery. For example, in Figure 7, there is shown the drug delivery by a bilayer magnetic vehicle.

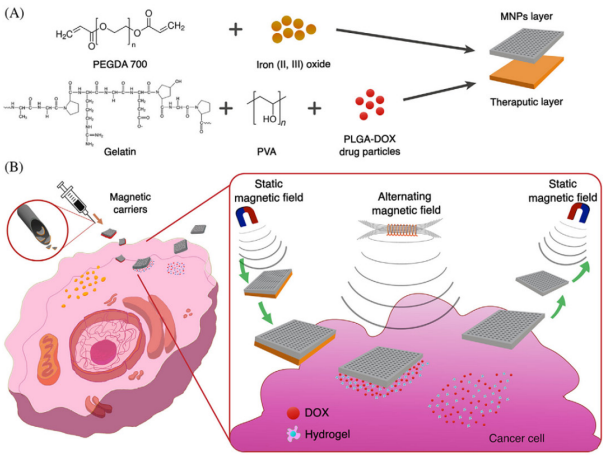

Figure 7) *(A) Bilayer magnetic drug delivery vehicle is composed of magnetic nanoparticle and DOX containing therapeutic layers. (B) Vehicles can be locally injected to the tumor site, which will then be delivered to the desired cancerous cell by a static magnetic field. Vehicle will be exposed to an alternating magnetic field, which will facilitate the release of the therapeutic layer. The remaining magnetic layer will be retrieved using a static magnetic field. Figure 6 from [21] – used with permission under terms of Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.*

The paper [22] provides an overview of the various applications of MNPs for cancer therapy including ones designed for utilizing them as drug delivery systems. The review [23] summarizes the recent advances in the synthesis and application of magnetic nanocrystal clusters; specifically describes the application of such clusters in drug delivery. In modern-day, the best emerging technology for targeted drug delivery uses magnetic iron oxide Fe_3O_4 nanoparticles. They have attracted considerable interest due to unique magnetic properties, biocompatibility and biodegradability. For example, core/shell MNPs based on an iron oxide core and a copolymer shell are found [24] to be smart nano-objects combining core super magnetic properties with shell drug carrier properties providing advanced features to the delivery of the anticancer drug DOX with spatial and temporal controls. Controlled and contactless movements of MNPs are crucial for their clinical application in drug targeting. And the key technological question is how to generate suitable magnetic fields on various length scales (μm–m).

It was presented [25] a system of permanent magnets which allows for steering of SPIONs on arbitrary trajectories observable by microscopy. The movement of the particles is simply controlled by rotation of permanent magnets cylindrical arrangements. The same instrument can be used to move suspended cells loaded with SPIONs along with predetermined directions. Surprisingly, it also allows for controlled movements of intracellular compartments inside of individual cells. The exclusive use of permanent magnets simplifies scaled up versions even for humans, which would open the door for remotely controlled *in vivo* guidance of nanoparticles or microrobots.

Rotational manipulation of MNPs chains or clusters offers a means for directed translation and payload delivery that should be explored for clinical use [26]. A Magneto Motive-System (MMS) was designed and constructed with a Helmholtz pair of coils on either side of a single perpendicular coil, on top of which was placed an acrylic tray having multiple parallel lanes (Figure 8). Several different MNPs were tested (for simultaneous and multichannel racing): velocities were determined in response to varying magnetic field frequency and amplitude. When DOX was chosen as the therapeutic agent, the MMS generated a maximal velocity of 0.9 cm/s. A rotating magnetic field conveniently generated by a three-coil electromagnetic device was used to induce rotational and translational movement of MNPs aggregates over mesoscale distances.

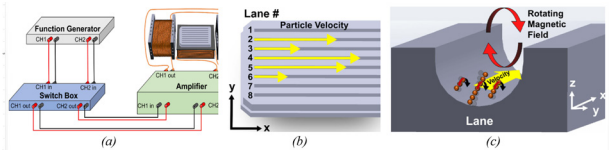

Figure 8) *Schematic of the MMS and basic principles of conducted experiments. (a) Electric components, coils and acrylic tray. (b) Acrylic tray illustration with numbered lanes and direction of MNPs movement. (c) Depiction of chains of magnetic nanoparticles rotating near the floor of a lane. Figures 4(A), 4(B) and 4(C) from [26] – originally published by and used with permission from Dove Medical Press Ltd.*

As is known, Magnetic-Resonance-Imaging (MRI) system navigation enables image-guided remote control of magnetically labeled therapies in the body. This technique comprises magnetic seeds navigated toward cancer cells through tissues in the body using magnetic propulsion gradients generated by an MRI scanner providing a safe means of treating hard-to-reach tumors [27].

Sustainable magnetic fields commonly used in targeted drug delivery are permissible for the magnetic nanocarriers. The most important limitation is related to the amount of leaving (in the body) MNPs that can cause side effects. In the study [28], it was proposed a bilayer hydrogel microrobot capable of retrieving MNPs after drug delivery that overcomes the above limitation. Such a bilayer hydrogel microrobot is composed of a MNPs layer and a therapeutic layer. Upon applying an alternating magnetic field at the target point, the therapeutic layer is dissolved to deliver drug particles, and then the MNPs layer can be retrieved using a magnetic field.

Synthesis of Ferromagnetic Clusters Doped Boron Nitride and Boron Carbide nanopowders

To obtain boron nitride and boron carbide nanopowders doped with ferromagnetic clusters, the corresponding research tasks should be set. To solve this problem, at first it is necessary to develop the methods for obtaining boron nitride and boron carbide nanosized powders and then the methods of their doping with ferromagnetic clusters. The general task is to obtain composites – boron compound/magnetic clusters in single technological cycles, which will facilitate process simplification and, consequently, increase the prospects of introducing such compounds into medical practice.

The synthesis of boron nitride and boron carbide nanopowders is expedient to be carried out using a liquid charge, which makes it possible

to use commercially available and relatively low-cost chemical reagents. Previously, authors have obtained nanopowders of boron nitride and boron carbide matrix ceramics of complex composition by similar methods. By modifying them, it will be possible to successfully implement the above tasks. Several different methods can be used to obtain magnetic clusters, including intercalation of iron compounds into boron nitride layered nanocrystals, magnetic phase CVD on the boron carbide nanopowder matrix surface, autoclave method and reduction of iron compounds to the metallic iron using various reducing agents, etc.

Task of development of methods of obtaining nanophase magnetic hexagonal boron nitride powder composite may include the following subtasks:

- Obtaining of boron nitride in ammonia atmosphere using boric acid based liquid charge;
- Development of methods of obtaining composite powder containing boron nitride and magnetic components Fe and Fe_3O_4;
- Intercalation of boron nitride using iron(3) chloride and iron(0) pentacarbonyl at temperature 200°C to 500°C in inert atmosphere and by autoclave method; etc.

As for the task of obtaining of nanocrystalline boron carbide using boron compounds, amorphous boron and organic precursors, it may include:

- Obtaining of preceramic precursors using boron compounds, B_2O_3 and H_3BO_3, and carbohydrates and obtaining nanocrystalline boron carbide powder from them by low-temperature carbidization method;
- Obtaining of boron carbide nanocrystalline powder using amorphous boron and organic precursors;
- Coating boron carbide powder with metallic Co and Fe using sodium borohydride ($NaBH_4$) in an organic solvent environment;
- Obtaining of boron carbide and iron/iron oxide composites using liquid charges; etc.

A chemical synthesis method of the BN nanopowders doped with magnetic clusters has been summarized by authors in the Report [29] (see also [30]). To obtain such nanopowders, two versions of the method were developed. In the first method, nanocrystalline boron nitride and pure nanoiron are obtained jointly in a single technological cycle. The starting components are sodium tetraborate, carbamide and ferric chloride. Their aqueous solution is sprayed over a quartz substrate preheated to 300°C. The resulting powder is annealed at 950°C from the beginning in ammonia and then in hydrogen atmospheres. As for the second method, it starts from the preparation of suspension solutions from preprepared nanocrystalline boron nitride and water-soluble iron salts, for example, iron chloride. For the purpose of homogenization and dehydration, the mixture is placed in a special mixer. The resulting mass is thermally treated from the beginning in air at 300°C, and then in a stream of hydrogen at 800°C until iron is reduced.

The nanocrystalline boron nitride needed in this approach was preprepared similarly to boron nitride nanopowders used for lubrication, i.e., by chemical methods from fluid charges [31-35]. Besides, boron nitride nanostructures formation can be based on concentrated light effect [36]. Another type of nanostructured boron nitride, so-called “metallic” boron nitride, is formed at very high temperature by melting boron-rich compounds in a BN-crucible [37].

Recently, authors have proposed [38] specially designed h-BN nanopowders added with ferromagnetic clusters Fe or Fe_3O_4 to provide a controlled delivery of BNCT agents under the magnetic field influence. Samples were synthesized by 3 methods.

(1) Vacuum exfoliatation of BN–$Fe(NO_3)_3$ complex obtained by ultrasonic treatment of

BN and Fe(3) nitrate suspension, its drying and heating at 250°C to 300°C (product contained 8–12 %Fe).

(2) CVD of iron or its oxide on pre-exfoliated BN matrix using iron pentacarbonyl and ferrocene for precursors (analogous approach allows obtaining of graphene based magnetic composites); BN:Fe composite can be obtained on BN layer held in $Fe(CO)_5$ vapor flow at 200°C, while adding of water vapor component yields BN:Fe_3O_4 compositions.

(3) Synthesis from a liquid charge (previously similar method used to obtain boron carbide-based composites containing cobalt Co): preparation of the paste from amorphous boron–organic compound–iron (cobalt) compound mixture, its pyrolisis at 200°C to 600°C and product treatment at 900°C to 1000°C in ammonia and hydrogen flow.

By applying the liquid charge chemical synthesis method, there are produced some boron carbide-based nanocomposites containing ferromagnetic components such as iron Fe and nickel Ni, namely, metal-ceramic nanocomposites containing boron carbide matrix and ternary metallic alloy binder in form of eutectic binary alloy Co–Ti, where Co partially is substituted by nickel Ni: B_4C/(Co–Ni–Ti) [39-43]. There are also synthesized nano powders of complex compositions, which in addition to boron carbide and cobalt contain metal diborides MeB_2 (Me = Ti or Zr, rarely Hf) and, maybe, tungsten carbide WC at high temperatures (>1600°C) tending to be converted into tungsten boride W_2B_5:B_4C–(Ti,Zr)B_2–Co and B_4C–(Ti,Zr)B_2–(WC,W_2B_5)/Co [41-50].

Conclusions

The present mini-review identifies the most effective among boron compounds drug delivery agents for BNCT, which is actively utilized for treatment of some aggressive cancers, where standard chemo- and radiation therapies are not able to work rigorously.

Currently, for neutron-absorbing centers – boron ^{10}B isotopes – delivery agents serve boron-containing organic macromolecules, which frequently are not able to provide sufficient content of boron in target tumor tissues. The attempts until done to overcome this problem mean the development of novel boron-containing nanosystems. From the recent literature analysis author' choice is made for boron nitride BN and boron carbide B_4C based drug delivery nanocarriers.

If BN and B_4C nanopowders are doped with ferromagnetic nanoclusters, constituent nanoparticles can be directly transported to tumor cells with exposure to an external magnetic field. This approach also is argued by a brief analysis of the latest literature available on the accumulation of therapeutically active agents in the target tissues under the magnetic field influence.

Based on authors' previous expertise in obtaining complex powder nanocomposites with boron nitride or boron carbide matrices by chemical methods, the synthesizing of boron nitride and boron carbide nanopowders doped with ferromagnetic nanoclusters is recommended to carry out from a liquid charge in a single technological cycle. Such approach will make it possible to use commercially available and relatively low-cost chemical reagents.

Thus, boron nitride and boron carbide nanopowders doped with ferromagnetic nanoclusters obtained by chemical synthesis from liquid charge will serve for effective and biocompatible boron ^{10}B isotope delivery agents in BNCT.

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