Nanobots: Future and Development

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DOI: 10.47750/pnr.2022.13.S03.293

Abstract

This review paper gives overview of the present status and further development in nanorobotics. Nanobots are very tiny machines designed to perform a specific task whose components are at or close to the scale of a nanometer. As consequence of nanotechnology, new technique consisting of device coming into market among these nanobots fields opportunity in cure of human illness. This bots are made of a single strand of DNA folded into desired shape. Bots will have two states – an "off" position, where the clamshells are closed tightly to bypass healthy cell without any damage and an "on" position, where clamshell opens up to expose cancerous cell from human body. In this paper included about method of working, composition, types, challenges in development and properties of nanobots.

Keywords: Nanobots, Nanotechnology, DNA nanobots.

1. INTRODUCTION

In 1959, physicist Richard Feyman was the first person to coin the term "nanobots". when he delivered the well-known lecture titled "There's plenty of room on the bottom". He commented about nanodips and nanobots for curing coronary heart disease.[1,2] Later, inspired by the discussion, scientist Eric Drexler published his book, "Engines of Creation." In cell biology, genetically programmable molecular machines have been mentioned as an emerging technology. [3] Robert Freitas was the person who conducted the initial investigation into nanobots.[4] Nanobots will be defined as a controllable nanoscale machine composed of a sensor and motor, successful with the aid of using acting specific tasks.[5] These aren't comparable to drones; rather, they are more like a complicated piece of fabric. [6]

The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization.[7] The design and building of nanorobots with sizes ranging from 0.1 to 10 m is the subject of a potential branch of engineering in nanotechnology. A nanorobot is a very small robot created to do an exact task at the nanoscale. They are also known as nanorobots or nanoids. The design of the nanorobots is inspired by biological models of bacteria. The major form of carbon likely employed in the creation of the nanorobot will be fullerence nanocomposites or diamond/diamondoid (which contains pure diamond and crystalline carbon allotropes). A nanorobot can be built using mechanical parts like bearings, gears, motors, and so forth. Diamondoid is probably going to be used to build the nanorobots' exterior shell due of its high thermal conductivity, strength, and inert nature. The likelihood of the body's immune system being activated may be reduced by the exceedingly smooth surfaces. Elements like silicon, hydrogen, sulphur, oxygen, and nitrogen might be used to create the nanoscale gears and other components created for specific uses. [8] Nanorobots will be the nanomachines that perform nanorobotic therapeutic treatments on each of the approximately 75 trillion cells that make up the human body to heal the damage that accrues as a result of metabolism (being alive). A nanorobot's substructures include its onboard power supply, sensors, nanocomputer, pumps, manipulators, and pressure tanks. [9] The ideal nanorobots will be able to connect with one another and create decentralization. Through a process known as self-replication, they will make many copies of themselves to replace damaged or worn out units. It can communicate with the doctor-dispensing nanorobot by encoding the messages to acoustic signals with a wave frequency of 1–100 MHz. These nanorobots can be removed after the task is finished either by active scavenger systems or the typical human excretory channels. [10,11] It is a nano robot machine, also known as a nanite, which is used to manipulate components with sizes ranging from 1 to 1000 nm. Nanometers are used to measure the dimensions of mechanical and electromechanical devices. Nanobots can construct with the atoms and molecules that make up our bodies because they are at micro level that they interact on a level equal to that of viruses and microbes. In order to monitor and provide more detailed information about the human body, nanobot can be equipped with a camera, a nano laser, and a nano chemical (to clean infected area). Additionally, nanobots can be managed both internally and externally to carry out a vast array of beneficial functions. Nanobots might carry out a range of comparable tasks, including as removing dead cells and tissues from a wound and promoting tissue growth to ensure a speedy and painless recovery without leaving an unsightly scar. Additionally, it can aid in the treatment of infected wounds that the effective medical Nanobot can quickly heal. [12, 13]

Nature has long given man a variety of medicinal herbs. Recent studies [14] have shown that some of these herbs have anticancer effects, and they are particularly beneficial when taken in the form of nanoparticles. [15,16] Nanoparticle formulations of cancer medications offer more benefits than traditional free pharmaceuticals. [17, 18]

2. Construction and Components of Nanobots

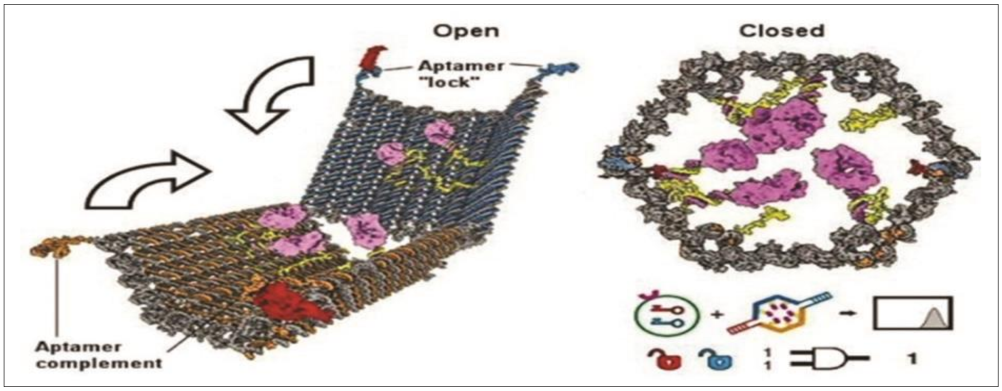

Fig. 1: open and close position

Nanobots constructed of DNA were created by Bachelet et al. [19] to act as a vehicle for cancer-treating medications. When these robots are inserted into the body, they kill carcinogenic cells only. These robots have a diameter of only 35 nm and are 200 times [20] smaller than a red blood cell. [21] The researchers utilized Cadnano, an open-source programme, to develop the nanorobots' structure [22]. They then used DNA origami to construct the bots. DNA origami is a method of creating intricately structured structures using DNA. [23-26] There are 12 locations for attaching payload molecules inside the bots. [21] There are two locations outside where aptamers can be attached (short nucleotide strands with special sequences for recognizing molecules on the target cell). The drug is inserted into the nanobot and molecular anchors hold it in place. When the aptamers detect their target, they serve as clasps, and the gadget opens up and discharges the payload. [27]

Nanorobots are made up of several different parts, including a power source, a fuel buffer tank, sensors, motors, manipulators, onboard computers, pumps, pressure tanks, and structural support. A nanorobot has the following substructures:

1. Payload- This void segment holds a small dose of drug/medicine. The nanorobots may want to transverse in the blood and release the drug to the site of infection/injury.

2. Micro camera- The nanorobot may include a miniature camera. The operator can steer the nanorobot when navigating through the body manually.[28,29]

3. Electrodes- The electrode mounted on the nanorobot. It could form the battery using the electrolytes in the blood. These distend electrodes could also kill the cancer cells by generating an electric current, and heating the cells up to death.

4. Lasers- These lasers could burn the harmful material like arterial plaque, blood clots or cancer cells.[29]

5. Ultra sonic signal generators- They used to target and destroy kidney stones.

6. Swimming tail- The nanorobot will require a means of propulsion to get into the body because of they travel against the flow of blood in the body.

Software called Nanorobot Control Design was created to simulate how nanorobots would behave in a fluid environment where Brownian motion would be dominant. [30] Swarm intelligence for decentralized activities is provided by the nanobots. Swarm intelligence algorithms are those created for nanorobot artificial intelligence. The behavior of social organisms like ants, bees, and termites, which cooperate without a centralized control, served as inspiration for the swarm intelligence technique. The three primary categories of swarm intelligence techniques developed are particle swarm optimization, artificial bee colonies, and ant colony optimization (PSO). [31]

3. Working of Nanobots

Logic gates with anaptamer encoding are used to control the nanobots. [19] Any kind of nanoparticle can be turned into autonomous bio-computing entities that can carry out Boolean logic gates (NAND, NOT, AND, and OR). Robotics and a wide range of logic circuits have benefited from DNA since it is a natural substrate for computation. [22] The functionality of logic gating is built into DNA, and logic gating is accomplished by input-induced breakdown of DNA structures. [32] DNA-based bio-computing in various forms has already been shown. Now, it has been demonstrated that DNA origami may be utilised to create nanoscale robots that can interact with one another dynamically when placed within the body. These interactions result in logical outputs that, upon detecting the target cell, are used to open or close nanobots to release the medicine.

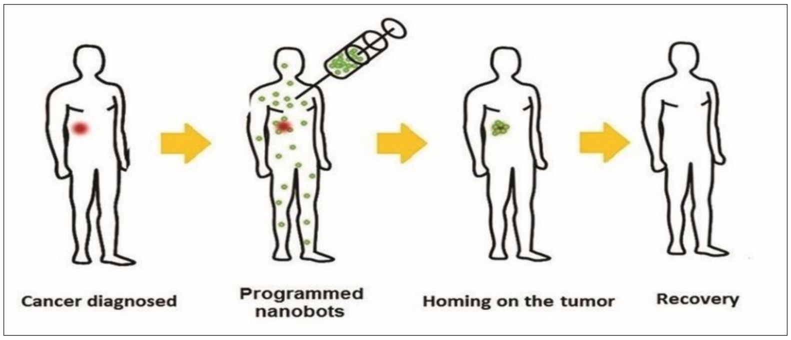

Fig 2: Recovery through nanobots

4. Types of Nanobots

Robert A. Freitas Jr. created the following kind of nanobots as artificial blood:

A. Respirocytes

B. Microbivores

C. Clottocytes

4.1 Respirocytes

Respirocytes are the nanorobots designed as artificial mechanical red blood cells. They have a 1 m diameter and are round, blood-borne particles. Diamondoid 1000 atm pressure vessels with reversible molecule-selective pumps make up the outer shell. [33, 34] Compared to natural red blood cells, respirocytes would oxygenate the body's tissues 236 times more.

The carbonic acidity could be controlled by the respirocyte's integrated nanocomputer and gas concentration sensors. [34] Through molecular pumps, the tank's contained gases are released from it in a regulated manner. The Respirocytes use molecular rotors to exchange gases. For a certain sort of molecule, the rotors have unique tips. [35] The Respirocytes are consisting of 18 billion atoms, which are carefully placed in 3 billion oxygen and carbon dioxide molecule-storage diamondoid pressure tanks. [33] Respirocytes transport carbon dioxide and oxygen molecules all over the body.

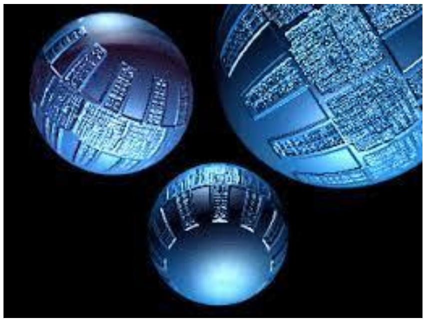

Fig: 3 An Artificial red blood cells: Respirocytes

A therapeutic dose of 5 cc of 50% Respirocytes saline suspension containing 5 trillion nanorobots would precisely replace the patient's whole 5.4 litres of blood's ability to carry gas. O2 partial pressure will be high and CO2 partial pressure will be low as the Respirocytes pass through the lung capillaries, therefore the onboard nanocomputer instructs the sorting rotors to load in oxygen and release carbon dioxide molecules. [29] The oxygen and carbon dioxide transport processes are mimicked by the Respirocytes, which act as an artificial erythrocyte. Three different types of rotors make up respirocytes. While moving through the body, one rotor releases the oxygen that has been accumulated. The third rotor absorbs glucose from the blood stream as a fuel source, whereas the second type of rotor absorbs all the carbon dioxide in the blood stream and releases it at the lungs. [35,36]

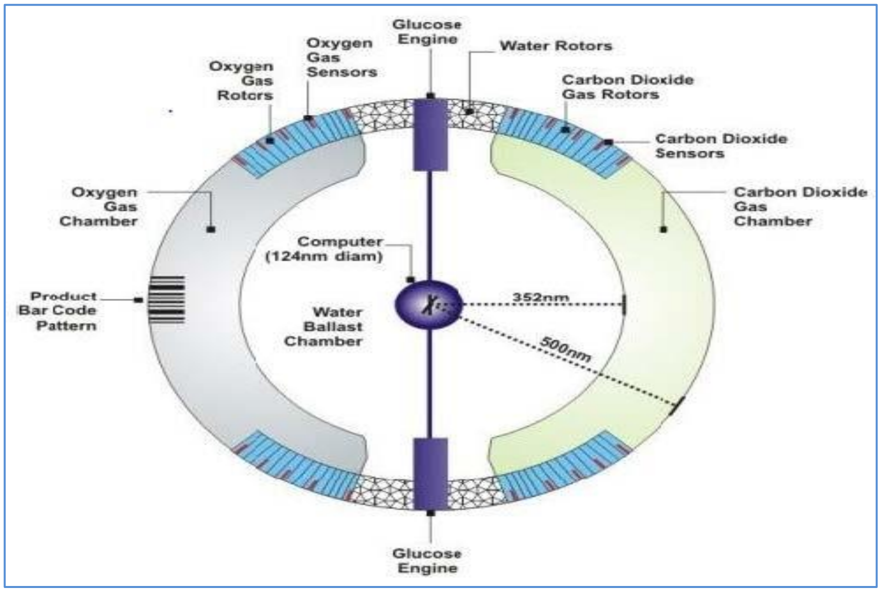

Fig: 4Internal structure of respirocyte

Since no other solid components of blood can sustain neutral buoyancy, they precipitate outwards during centrifugation. Back into the filtered plasma goes the blood components. The centrifuged solid blood components are mixed with the filtered plasma before being safely reintroduced back into the patient's body. [33]

4.2 Microbivores

Microbivores are nanorobots, also referred to as nanorobotic phagocytes, which serve as artificial white blood cells. By using the phagocytosis process, microbivores primarily function to absorb and digest pathogens in the blood stream. The microbivore is a spheroid device constructed of sapphire and diamond that has 610 billion carefully ordered structural atoms and measures 3.4 mm in diameter along its major axis and 2.0 mm in diameter along its minor axis. It breaks down into smaller molecules and captures the infections already present in the blood stream. The microbivore is made up of four essential parts:

I. An array of reversible binding sites.

II. An array of telescoping grapples.

III. A morcellation chamber.

IV. Digestion chamber [37]

The nine separate antigenic markers should each be distinct and confirm a positive binding event that indicates the presence of the target microorganism. Nine marker sets would be disseminated in 20,000 copies among the microbivore's 275 disk-shaped zones. In 30 seconds, the microbivore will have completed its entire phagocytosis cycle. As the bacterial components are swallowed and digested into non-antigenic bio molecules, there are no chances of septic shock or sepsis. [37] White blood cells treated with antibiotics act 1000 times more slowly than a microbivore, and the pathogen has little possibility of developing multidrug resistance. They can be used to treat infections in the urine and synovial fluids, as well as respiratory and cerebrospinal infections.

4.3 Clottocytes

When platelets affect the endothelial cells of a blood vessel, the result is hemostasis, or blood clotting. Collisions between exposed collagen from broken blood arteries and the platelets can activate them. Natural blood clotting might take anywhere between 2 and 5 minutes to complete. The use of corticosteroids during treatment might cause allergic responses, hormonal secretions, and blood/platelet damage to the lungs. [31] At 20 clottocytes per cubic millimetre of blood, or about 1/10,000th the concentration in the blood stream, the clotting activity of clottocytes is essentially similar to that of natural platelets. [38]

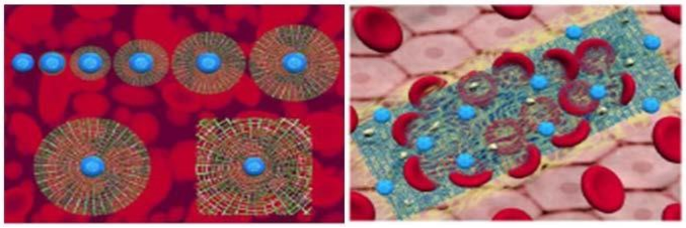

Fig:5 Blood clotting mechanism of clottocytes

Reliable communication protocols would be necessary to manage multi-device activation radius within the local clottocyte population as well as to coordinate mesh release from neighbouring clottocytes. At human body temperature, oxygen molecules from the air diffuse through serum if the first clottocyte is 75 m from the air-serum contact. Rapid sonic pulses from this detection were sent to the nearby clottocytes. This enables the carefully planned device-enablement cascade to spread quickly.

5. Properties

Organic materials like polynucleotides and proteins as well as inorganic materials like metals and diamond can be used to make nanobots. [39,40]

Nanobot's solubility and interactions with other macromolecules or cell surfaces are significantly influenced by their surface characteristics. This is particularly noteworthy in the case of diamond due to its extreme strength and effectiveness. Silver, for example, is a metal that may serve two roles. It can serve as the building block for nanobots and be antimicrobial. [41-43] in some cases, they can act as a virus causing irreversible cell damage. [44] The motion, permeability, and reactivity of nanobots are directly influenced by their size and form. [45] One could employ various extracellular nanostructures as models. Ga et al's [46] effective propulsion in biological conditions was accomplished using spiral water-conducting plant vessels that were thinly covered in Ti and Ni layers. [46] The propulsion system might be biocompatible or not depending on the fuel used. [47-48]

6. Design and Development Challenges

This section will discuss the various challenges in the design and development of nanorobots.

General challenges faced in the development of nanorobots, regardless of their applications, involve:

- DNA approach that cannot be employed to develop complex devices, and

- Bacteria-based nanorobots, incorporating bacteria in the building of nanorobots, present a serious challenge, as bacteria is a living organism and therefore inappropriate due to safety reasons. Performance-wise, nanorobots depend on Brownian motion and electrical noise.[49,50,51]

- Positional nano assembly that is inefficient in regards to building nanodevices, and this method does not incorporate nanoelectronics.

Table: 1 Comparison between architecture of macro robots and nanorobots

Architecture	**Macro Robots**	**Nano Machines**
Sensors	Temperature sensors, Light sensors, Force sensors	CMOS sensors, Nanotubes, Nanowires, Biosensors
Actuators	Pneumatic motors, Hydraulic and Electric motors	Flagella motors, DNA and RNA actuators, Protein-based motors (ATP), Liquid-crystal Elastomers (LCE's)
Navigation components	Ball bearings, Belt drives, Gears	β Sheets, sperm-like motors
Joints and Links	Prismatic, Spherical, Revolute, Cylindrical	Synthetic joints, Molecular Bonds, DNA hinges, and Nanotubes

New methods of integrating all these together to control the response or actions of a nanorobot should be proposed, For example, a different imaging techniques can be used to localize the nanorobot inside the body, and that information can be used by the control system to send commands to the actuators or to navigate the nanorobot using variable magnetic fields. The traditional method of reading sensors, processing the information, and designing a control scheme to send commands to actuators to minimise the error between the desired and actual values of a parameter (e.g., velocity, position, etc.) might not be feasible to be used. The development of nanoscale components is essential to the construction of a nanorobot; however, this is hindered by technological limitations.[52] The fabrication of a nanorobot and its application in nanomedicine is limited by two main factors: (1) the status of current technological advancements; and (2) The limitations of a nanorobot to work in micro fluids.[52]

The first limitation has been overcome by the design and hardware control based on the progress of nanomechatronics, and with the rapid increase in advancements in nano-biotechnology, molecular manufacturing has led to the development of small-scale devices. These devices form an integral part of the nanorobot and are comprised of the main elements for sensing, actuation, the transmission of data, power supply, and control [53-56].

The second limitation—to incorporate a nanorobot in a fluidic environment—has been a critical challenge in the field of nanorobotics and its application in medicine. Therefore, various studies have shifted towards the development of microbots (A.K.A. microrobots), broadly referred to as “swimmers”. Microbots are like their natural counterpart, and they perform well only in the presence of a nutrition or energy supply.[57]

7. Nanobots in Future

Frankly, nanorobotics holds such a vast scope, that a single paper can't cover it all. Hence, the focus here is limited only to its revolutionary impact on the field of medicine.

7.1 Central Nervous System (CNS): Nanobots could be used to treat the cancers in the CNS too. At times, they themselves could act as implants, replacing damaged neurons in some patients. Nanobots will also be able to perform neural surgeries as well as surgeries of the brain, with a high success rate. It would also prevent the necessity of today: drilling a hole in the skull to gain access to the brain. Nanobots can also be used to help people suffering from motor neuron diseases, as well as paralysis. Once injected into the patient, they can locate themselves at specific places in the brain, and pick up impulses which would normally be delivered to the body's motor neurons. These impulses can be used to drive external prosthetics, such as a robotic arm. Thus, it would help a lot of people from overcoming their disabilities.

7.2 Body surveillance: Continuous monitoring of vitals and wireless transmission could be possible using nanobots, leading to a quantum leap in diagnostics. This would also help in rapid response in case of sudden change in vitals or could warn against a possibility of a risk, such as high blood glucose in case of diabetics. Also multi-functional bots could convert themselves into stents; say to open up a blockage in an artery. The bot itself can be used as a tool, to remove unwanted materials such as blockages in the circulatory system. Nanobots could be used in large quantities inside the body to sense and repair anomalies/abnormalities. Current macroscopic robots are being programmed and tested with what is known as "swarm intelligence" in which they share information available to each one of them, pool it together, and take collective decisions. Such behaviour is seen in ant colonies too; they communicate with the help of chemicals and behave like one large organism, often referred to as a "super organism". Using the strategy of swarm intelligence, in\ intra-body nanobots could help in creating a single strong defensive shield against pathogens and toxins. It would also help prevent vitals from going out of medically defined bounds.

7.3 Delicate surgeries: Surgeries such as those of the eye are even today performed successfully only by a few skilled surgeons. Immense risk is involved in these delicate surgeries and they require a steady hand as well as a strong constitution. It may soon be possible to take the human element of risk out of this equation. Micro surgery of the eye as well as surgeries of the retina and surrounding membranes could soon be performed using nanobots. In addition, instead of injecting directly into the eye, nanobots could be injected elsewhere in the body and guided to the eye to deliver drugs, if necessary. Similarly, other difficult surgeries will also benefit from advances in nanorobotics. Foetal surgery, risky even today due to high mortality rate of either the baby or the mother, could soon have a 100% success rate, due to the fact that nanobots can provide better access to the required area inducing minimal trauma.

7.4 Cancer treatment: This is probably the main reason for the development of nanorobotics. Drug delivery for cancer today is difficult to control. Chemotherapy harms healthy tissue in addition to cancerous tissue. We cannot prevent adverse effects of chemotherapy on other parts of our body. Nanorobotics will change it all. Nanobots could be used to deliver drugs specifically to the tumour only, thus preventing the peripheral impact of the drug. One of the many methods to achieve this is the following: Primary nanobots are sent to the target tissue (tumour) to inflame it. This is partly a machine gun approach; a lot of the bots will be wasted. However, only the tumour is inflamed and not any other tissue in the entire body. Now, a second wave of bots is sent, to target the inflamed tissue. This wave of bots contains the actual chemotherapy drug. It releases its payload i.e. the drug only after sensing the inflamed tissue. Thus, we have a highly concentrated targeted action, with no peripheral impact. We could liken it to a sniper's rifle.

8. Conclusion

Nanobots can improve dental and cancer treatments, healthcare and human life better than several developments of past. Other application such as, Better filters for water purification, more effective methods of delivering drugs in medicine and new ways of repairing damaged tissue and organs.It could also be potentially beneficial for the environment, for example, to create fuel cells, to remove heavy metals, cyanide and other substance that damage the environment. By 2030, nanobots are project to advance towards amazing breakthroughs in healthcare. By then, tiny nanobots will float through our bloodstream on a mission to prevent sickness. The technology already tested in animals, where nanobots are set out to destroy cancer cells. Researchers believe that nanobots could soon deliver drugs to humans with a high degree of accuracy. This would allow for delivery of micro dosages right where the patient needs them, and could help prevent harmful side effects. In the future, nanotechnology could also enable objects to harvest energy from their environment. New nano-materials and concepts currently developed that show potential for producing energy from movement, light, variations in temperature, glucose and other sources with high conversion efficiency.

REFERENCES

1. Freitas Jr RA. What is nanomedicine?. Nanomedicine: Nanotechnology, Biology and Medicine. 2005 Mar 1;1(1):2-9.
2. Ahmad U, Md F. Smart nanobots: The future in nanomedicine and biotherapeutics. J Nanomedine Biotherapeutic Discov. 2016;6:e140.
3. Jones R. Biology, Drexler, and nanotechnology. Materials Today. 2005;8(8):56.
4. Freitas Jr RA. A mechanical artificial red cell: exploratory design in medical nanotechnology. Artificial Cells, Blood Substitutes, and Immobilization Biotechnology. 1998;26:411-30.
5. Christian Martin, Put more nano in robotics. Nature Nanoechnology. 2014;(9)556
6. Tucker P. Nanobots to fight cancer. The Futurist. 2012 May 1;46(3):15.
7. Motoyama Y, Appelbaum R, Parker R. The National Nanotechnology Initiative: Federal support for science and technology, or hidden industrial policy?. Technology in Society. 2011 Feb 1;33(1-2):109-18.
8. Uriarte, S. L., “Nanorobots” [online] Technical report EscuelaSuperior De Ingenieros De Bilbao, BilbokoIngeniarienGoiEskola, Universidad Del País Vasco / EuskalHerrikoUnibersitatea. 2011, http://nano-bio.ehu.es/files/nanorobots_work.pdf
9. Abeer S. Future medicine: nanomedicine. Jimsa. 2012 Sep;25(3):187-92.
10. Kharwade M, Nijhawan M, Modani S. Nanorobots: A future medical device in diagnosis and treatment. Research Journal of Pharmaceutical, Biological and Chemical Sciences. 2013 Apr;4(2):1299-1307.
11. Sujatha, V., M., Suresh, and Mahalaxmi, “Nanorobotics - afuturistic approach”, Indian journal of Dentistry, 1(1):86-90, 2010.
12. Yao C, Lu J. Introduction to nanomedicine. Nanomedicine: Technologies and Applications. 2012.3–19
13. Mitra M. Medical nanobot for cell and tissue repair. Int Rob Auto J. 2017;2(6):00038.
14. Tripathi PA, Singh AD. Natural resources from plants in the treatment of cancer: an update. Asian J Pharm Clin Res. 2017;10(7):13-22.
15. Preethi R, Padma PR. Anticancer activity of silver nanobioconjugates synthesized from Piper betle leaves extract and its active compound eugenol. Int J Pharm Pharm Sci. 2016;8(9):201-5.
16. Vijay M, Anu Y. Anticancer activity of camellia Sinensis mediated copper nanoparticles against HT-29, MCF-7, and MOLT-4 human cancer cell lines. Asian J Pharm Clin Res. 2017;10(2):71-.
17. Hemant K, Raizaday AB, Sivadasu PR, Uniyal SW, Kumar SH. Cancer nanotechnology: nanoparticulate drug delivery for the treatment of cancer. Int J Pharm Pharm Sci. 2015;7:40-6.
18. Goldberg MS. Immunoengineering: how nanotechnology can enhance cancer immunotherapy. Cell. 2015 Apr 9;161(2):201-4.
19. Douglas SM, Bachelet I, Church GM. A logic-gated nanorobot for targeted transport of molecular payloads. Science. 2012 Feb 17;335(6070):831-4.
20. Raaja DK, Ajay V, Jayadev SG, Kumar M, Karthikeyan NS, Ravichandran C. Mini review on nanobots in human surgery and cancer therapy; 2016.
21. Nikitin MP, Shipunova VO, Deyev SM, Nikitin PI. Biocomputing based on particle disassembly. Nature nanotechnology. 2014 Sep;9(9):716-22.
22. Katsnelson A. DNA robot could kill cancer cells. Nature. 2012 Feb 16:1-3.
23. Rothemund PW. Folding DNA to create nanoscale shapes and patterns. Nature 2006;440:297-302.
24. Jiang Q, Song C, Nangreave J, Liu X, Lin L, Qiu D, Wang ZG, Zou G, Liang X, Yan H, Ding B. DNA origami as a carrier for circumvention of drug resistance. Journal of the American Chemical Society. 2012 Aug 15;134(32):13396-403.
25. Lund K, Manzo AJ, Dabby N, Michelotti N, Johnson-Buck A, Nangreave J, Taylor S, Pei R, Stojanovic MN, Walter NG, Winfree E. Molecular robots guided by prescriptive landscapes. Nature. 2010 May;465(7295):206-10.
26. Fu J, Yan H. Controlled drug release by a nanorobot. Nature biotechnology. 2012 May;30(5):407-8.
27. Devasena U, Brindha P, Thiruchelvi R. A review on DNA nanobots: A new techniques for cancer treatment. Asian J Pharm Clin Res. 2018;11(6):61-4.
28. Kharwade M, Nijhawan M, Modani S. Nanorobots: A future medical device in diagnosis and treatment. Research Journal of Pharmaceutical, Biological and Chemical Sciences. 2013 Apr;4(2):1299-307.
29. Mishra J, Dash AK, Kumar R. Nanotechnology Challenges; Nanomedicine: Nanorobots. International Research Journal of Pharmaceuticals. 2012;2(4):112-9.
30. Sharma NN, Mittal RK. Nanorobot movement: Challenges and biologically inspired solutions. International journal on smart sensing and intelligent systems. 2008 Mar 1;1(1):87.
31. Boonrong P, Kaewkamnerdpong B. Canonical PSO based nanorobot control for blood vessel repair. International Journal of Biomedical and Biological Engineering. 2011 Oct 25;5(10):473-8.
32. Katsnelson A. DNA robot could kill cancer cells. Nature. 2012 Feb 16:1-3.
33. Freitas RA. Current status of nanomedicine and medical nanorobotics. Journal of computational and theoretical nanoscience. 2005 Mar 1;2(1):1-25.
34. Freitas Jr RA. Medical nanorobotics: the long-term goal for nanomedicine. Nanomedicine design of particles, sensors, motors, implants, robots and devices. Artech House, Norwood Ma. 2009:367-92.
35. Arpita J, Hinali T, Stanukumar B, Krunali T, DB M. Nanotechnology revolution: respirocytes and its application in life sciences. Innovare Journal of

Life Science. 2013;1(1):8-13.
36. Frcitas RA. Exploratory design in medical nanotechnology: a mechanical artificial red cell. Artificial Cells, Blood Substitutes, and Biotechnology. 1998 Jan 1;26(4):411-30.
37. Eshaghian-Wilner MM, editor. Bio-inspired and nanoscale integrated computing. John Wiley & Sons; 2009 Sep 22.
38. Kannan TT, Lal AH, Ganesan M, Baskaran R. Study and Overview About Molecular Manufacturing System. International Journal of Mechanical Engineering and Robotics Research. 2013;2(1):193-201.
39. Freitas Jr RA. What is nanomedicine?. Nanomedicine: Nanotechnology, Biology and Medicine. 2005 Mar 1;1(1):2-9.
40. TT Vu, UM Braga-Neto Is Bagging Effective in the Classification of Small-Sample Genomic and Proteomic Data? 2009(1)
41. Cristea PD, Daugherty E, Shmulevich I, Chen J, Wang ZJ. Representation and analysis of DNA sequences. Genomic Signal Processing and Statistics. 2005;2:15-66.
42. Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramírez JT, Yacaman MJ. The bactericidal effect of silver nanoparticles. Nanotechnology. 2005 Aug 26;16(10):2346.
43. Franci G, Falanga A, Galdiero S, Palomba L, Rai M, Morelli G, Galdiero M. Silver nanoparticles as potential antibacterial agents. Molecules. 2015 May 18;20(5):8856-74.
44. Toumey C. Nanobots today. Nature nanotechnology. 2013 Jul;8(7):475-6.
45. Kim JS, Kuk E, Yu KN, Kim JH, Park SJ, Lee HJ, Kim SH, Park YK, Park YH, Hwang CY, Kim YK. Antimicrobial effects of silver nanoparticles. Nanomedicine: Nanotechnology, biology and medicine. 2007 Mar 1;3(1):95-101.
46. Simeonidis K, Mourdikoudis S, Kaprara E, Mitrakas M, Polavarapu L. Inorganic engineered nanoparticles in drinking water treatment: a critical review. Environmental Science: Water Research & Technology. 2016;2(1):43-70.
47. Gao W, Feng X, Pei A, Kane CR, Tam R, Hennessy C, Wang J. Bioinspired helical microswimmers based on vascular plants. Nano letters. 2014 Jan 8;14(1):305-10.
48. Dalai DR, Bhaskar D, Agali C, Singh N, Gupta D, Bumb S. Futuristic application of nano-robots in dentistry. Int J Adv Health Sci. 2014 Jul;1(3):16-20.
49. Dalai DR, Bhaskar D, Agali C, Singh N, Gupta D, Bumb S. Futuristic application of nano-robots in dentistry. Int J Adv Health Sci. 2014 Jul;1(3):16-20.
50. Raj AR, Vijayalekshmi NG, Akhila S. Nanorobots-Medicine Of The Future. PharmacieGlobale. 2012 Dec 1;3(12):1.
51. Freitas Jr RA. What is nanomedicine?. Nanomedicine: Nanotechnology, Biology and Medicine. 2005 Mar 1;1(1):2-9.
52. Jiang HW, Wang SG, Xu W, Zhang ZZ, He L. Construction of medical nanorobot. In2005 IEEE International Conference on Robotics and Biomimetics-ROBIO 2005 Jul 5 (pp. 151-154). IEEE.
53. Schmidt CK, Medina-Sánchez M, Edmondson RJ, Schmidt OG. Engineering microrobots for targeted cancer therapies from a medical perspective. Nature Communications. 2020 Nov 5;11(1):1-8.
54. Soto F, Wang J, Ahmed R, Demirci U. Medical Robotics: Medical Micro/Nanorobots in Precision Medicine (Adv. Sci. 21/2020). Advanced Science. 2020 Nov;7(21):2070117.
55. Upadhyay VP, Sonawat M, Singh S, Merugu R. Nano robots in medicine: A review. Int. J. Eng. Technol. Manag. Res. 2017;4(12):27-37.
56. Cavalcanti A, Shirinzadeh B, Freitas RA, Hogg T. Nanorobot architecture for medical target identification. Nanotechnology. 2007 Nov 29;19(1):015103.
57. Peyer KE, Zhang L, Nelson BJ. Bio-inspired magnetic swimming microrobots for biomedical applications. Nanoscale. 2013;5(4):1259-72.