Reviews UDK 57.086.15:626.8
doi: 10.7251/COM1201026J

NANOTECHNOLOGY AND WATER

K. K. Jain[*]
FRACS, FFPM, CEO, Jain PharmaBiotech
Blaesiring 7, CH-4057 Basel, Switzerland

Abstract: In this paper the role of nanobiotechnology in the study of biological systems in water environment is presented. The functional nano-meter-scale structures in the cell such as genetic material, membranes, enzymes and molecular machines are decribed. The knowledge gained has applications in nanomedicine. Nanoparticles have practical applications in detection of water pollution and water purification, which is of public health importance worldwide.
Keywords: water, purification, nanobiotechnology, biomarcers, nanomedicine.

1. INTRODUCTION

Nanotechnology implies the creation and utilization of materials, devices, and systems through the control of matter on the nanometer-length scale [1−9], i.e. at the level of atoms, molecules, and supramolecular structures. Given the inherent nanoscale functional components of living cells, nanotechnology has inevitably found applications in biotechnology giving rise to the term nanobiotechnology. Nanobiotechnology has contributed to advances in our understanding of biology, which has applications in health sciences as described in the "Handbook of Nanomedicine" [5]. An important application is refinement of molecular diagnostics to detect single bacteria or virus particles.

2. NANOBIOTECHNOLOGY FOR STUDY OF BIOLOGICAL SYSTEMS

This review will start with the role of nanobiotechnology in the study of biological systems in a water environment, e.g. functional nanometer-scale structures in the cell such as genetic material, membranes, enzymes and molecular machines.

2.1. Nanobiotechnology at single cell level

Molecules in the cell are organized at nanometer scale. Visualizing the dynamic change in these molecules and studying the function of cells is one of the challenges in nanobiotechnology. A single molecule is the ultimate nanostructure. Single molecule microscopy and spectroscopy are some of the techniques used to study single molecules.

A single cell is an ideal sensor for detecting various chemical and biochemical processes, and manipulation of cells can be better done through mechanical rather than biochemical means.

2.2. Water droplet as a nanoscale device

A single cell, or even a subcellular structure, e.g., an organelle, is captured within a droplet on the microfluidic device [2]. This nanoscale laboratory enables one to do an experiment in the droplet on one cell or even a few molecules. This makes it easier to get a wide range of information about a cell and to study the structure and the form simultaneously.

Such a device has water in one channel and oil in the other; whereas the target is encapsulated as the water droplet forms as shown in Figure 1. A powerful laser microscope is used to study the contents and examine chemical processes and a laser beam is used to manipulate the cell or even just a few molecules, combining them with other molecules to form new substances.

Expanding the current detection schemes from optical techniques to mass spectrometric methods is another possibility that will greatly expand the scope of single-cell analysis.

[*] Corresponding author: jain@pharmabiotech.ch

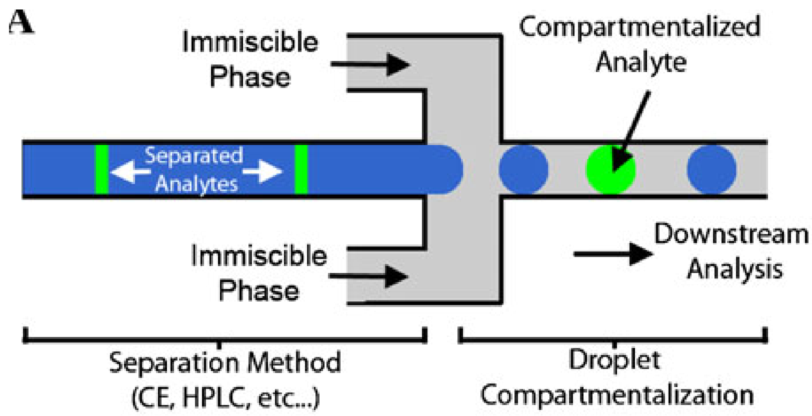

Figure 1: Water droplet as nanoscale device

3. SCOPE OF APPLICATIONS OF NANOBIOTECHNOLOGY RELEVANT TO WATER

Nanoparticles (NPs) have practical applications in detection of water pollution and water purification, which are of public health importance worldwide. A water droplet can be used as a nanoscale test tube for analysis and experimentation at unprecedented tiny scales. Such a microfluidic device can capture a single cell, or even a small subcellular structure called an organelle within a droplet.

Nanotechnology can contribute to improving water quality, availability, and viability of water resources. Within the category of sensing and detection, the development of new and enhanced sensors to detect biological and chemical contaminants at very low concentration levels in the environment, including water, is of particular interest. Bioactive nanoparticles have application in water treatment, purification and disinfection.

4. NANOMATERIALS AND WATER

There are numerous nanomaterials, most of which are NPs. Carbon nanotubes and dendrimers, which are relevant to the topic of water, will be described briefly as examples and details can be seen in the Handbook of Nanomedicine [5].

4.1. Carbon nanotubes

Carbon nanotubes (CNTs) are rolled-up sheets of carbon atoms that appear naturally in soot, and are central to many nanotechnology projects. These nanotubes can be as small as 1 nm in diameter, with the length reaching several microns. They are stronger than any other known material in the universe. CNTs can be single-walled (SWCNT) when composed of a single plane of graphene or multi-walled carbon nanotubes (MWCNT), which have multiple concentric layers. Synthesized nanotubes can be used as smart nanophase extraction agents, e.g. to remove drug molecules from solutions.

Filling of hydrophobic CNTs by water has been observed both experimentally and from simulations. Free energy extracted from molecular dynamics simulations of water confined in CNTs (0.8-2.7 nm ⌀) was studied [7]. Water inside CNTs was found to be more stable than in the bulk, but thermo-dynamic properties change dramatically with CNT diameter. Other findings of this study were: (i) thermodynamic property stabilized, vapor-like phase of water for small CNTs (0.8–1.0 nm); (ii) thermodynamic potential stabilized, ice-like phase for medium-sized CNTs (1.1–1.2 nm); and (iii) a bulk-like liquid phase for CNTs larger than 1.4 nm. Free energies and sequence of transitions are considered to arise from the tetrahedral structure of liquid water. These results form a basis for understanding water transport through nanostructures that occurs in nanofiltration and desalination.

4.2. Dendrimers

Dendrimers (dendri - tree, mer - branch) are a novel class of 3D nanoscale, core-shell structures that can be precisely synthesized for a wide range of applications while specialized chemistry techniques enable precise control over their physical and chemical properties. They are constructed generation by generation in a series of controlled steps that increase the number of small branching molecules around a central core molecule. Up to ten generations can be incorporated into a single dendrimer molecule. The final generation of molecules added to the growing structure makes up the polyvalent surface of the dendrimer.

Dendrimers are basic building blocks that enable specific nanostructures to be built to meet the existing needs and solve the evolving problems.

5. NANODIAGNOSTICS FOR DETECTION OF POLLUTANTS AND PATHOGENS IN WATER

Because of the small dimension, most of the applications of molecular diagnostics fall under the broad category of biochips/microarrays. Polymerase chain reaction (PCR) can introduce artifacts caused by the preferential amplification of certain sequences. Alternative label-free methods such as surface plasmon resonance rely on mass detection. The application of nanotechnology has refined molecular diagnosis, also termed nanodiagnosis. Nanoparticles, used as tags or labels, increase the sensitivity, speed and flexibility of biological tests.

Nanodiagnosis enables detection of trace substances, even single molecules that are missed by other tests. Measurement devices based on nanotechnology can make thousands of measurements rapidly and inexpensively.

An example is a fast as well as sensitive test for E. coli O157:H7 that combines ligand magnetic nanoparticles (LMNPs) with fluorescent silica nanoparticles (FSiNPs) and is performed as a 2-color flow cytometry assay [4]. The detection sensitivity is greatly improved by LMNPs enrichment and signal amplification of the FSiNPs labeling. This assay enables detection of E. coli O157:H7 in levels as low as 7 cells mL(-1) in <4 h. This method has potential applications demanding high sensitivity bacterial identification, e.g., in drinking water supply.

The evolution of diagnostics in the era of nanotechnology is shown in Figure 2.

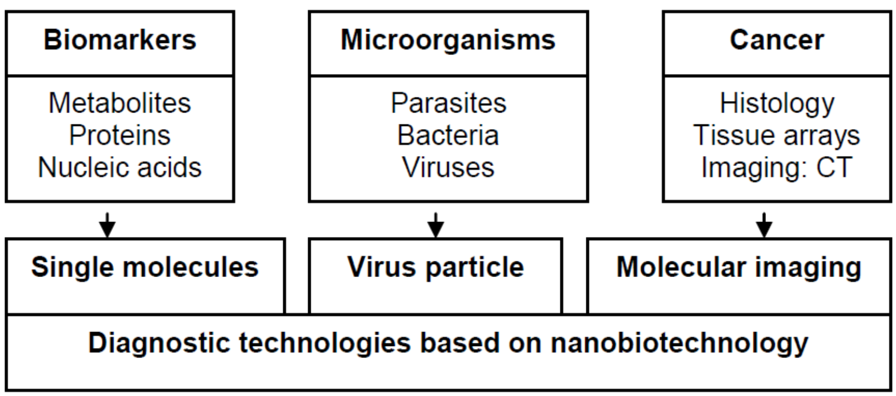

Figure 2: Evolution of diagnostics in the era of nanotechnology

6. NANOTECHNOLOGY FOR WATER PURIFICATION

Nanotechnology has a potential to provide novel nanomaterials for treatment of surface water, groundwater, and waste water contaminated by toxic metal ions, organic and inorganic solutes, and microorganisms. These consist of:

– Nanomaterials for water filtration,
– Nanotechnologies for water remediation,
– NPs for disinfection of water,

6.1. Nanofiltration to remove viruses from water

Nanofiltration is a relatively simple and reliable procedure that consists of filtering water through membranes with nanopores (size 15-40 nm) that retain viruses by size exclusion.

The shortcomings of some membranes are that they often form pin-holes and cracks during the fabrication process, resulting in wasted membranes. Scientists at the Queensland University of Technology (QUT) in Australia have developed specially designed ceramic membranes used as nano-mesh for nanofiltration, which are less likely to be damaged during manufacture and have a potential to remove viruses from water. This modification has increased the rates of the flow passing through the membranes 10-fold compared with current ceramic membranes, while maintaining the efficiency of capturing over 96% of the unwanted particles.

6.2. Nanostructured membranes for water purification

Current methods for the purification of contaminated water sources are chemical-intensive, energy-intensive, and/or require post-treatment due to unwanted by-product formation.

The integration of nanostructured materials and Fe-catalyzed free radical reactions enables detoxification of water. Harmful organic contaminants can be degraded through the addition of a substrate, glucose, which is enzymatically converted to H_2O_2 without adding harmful chemicals [6]. The application of these technologies can be extended to disinfection and/or virus inactivation.

6.3. Nanotechnologies for water remediation

Advantages of use of nanomaterials for water remediation include their enhanced reactivity, surface area and sequestration characteristics. Several nanomaterials are in development for this purpose including the following:

-Biopolymers
-Carbon nanotubes
-Iron nanoparticles
-Zeolites

Cyanobacterial metabolites -- microcystin, cylindrospermopsin (CYN), 2-methylisoborneol (MIB) and geosmin (GSM) -- are a major problem for the water industry. Low molecular weight cut-off (MWCO), or 'tight' NF, membranes afford average removals above 90% for CYN, while removal by higher MWCO, or 'loose' NF membranes is lower. MIB and GSM are removed effectively (>75%) by tight NF but less effectively by loose NF. Microcystin variants are removed to above 90% by tight NF membranes; however, removal using loose NF membranes depends on hydrophobicity and charge of the variant. Natural organic matter concentration in the waters treated with this method had no effect on the removal of cyanobacterial metabolites [3].

Several NPs have been shown to have antibacterial effects and are used as disinfectants, e.g. silver NP coated on surfaces. A study has shown that lanthanum calcium manganate (LCMO) NPs have greater antibacterial efficacy against P. aeruginosa-ATCC 27853, a soil and water born pathogenic bacteria as compared to Eu3+ doped lanthanum calcium manganate (LECMO) NPs [2]. Size of synthesized NPs was 50-200 nm and X-ray diffraction pattern showed the formation of a single phase LCMO or LECMO of an orthorhombic crystal structure after annealing the precursor at 10000 C for 2 h in the air. LCMO NPs can offer future applications as antimicrobial drugs and for water purification.

Iron oxide (α-Fe(2)O(3)) nanoparticles, 5nm in size, have been used to remove arsenic ions from natural water samples [8]. At low equilibrium arsenic concentrations, they are effective in removing both As(III) and As(V) from water samples. Iron nanoparticles maintained their arsenic adsorption capacity even at very high competing anion concentrations. This method was used to purify contaminated natural lake water sample to meet the United Stated Environmental Protection Agency's drinking water standard for arsenic.

6.4. Nanotechnology-based photochemical water purification

Nanotechnology-based photochemical water purification is also feasible. Bioactive nanoparticles can be used for disinfection of water, e.g., metal-oxide NPs, particularly silver, and titanium dioxide for photocatalytic disinfection can provide an alternative to chlorination of water.

Multiple wavelengths of LED or natural light illuminate a high-surface-area nanotechnology coating to cause photochemical reactions. In development by Puralytic Inc, this process effectively removes the broadest range of contaminants including:

-Organic compounds: pharmaceuticals, petrochemicals.

-Heavy metals: lead, mercury, arsenic, and selenium

-Microorganisms: viruses, bacteria, protozoa, cysts

The process is environmentally friendly and cost-effective with:

-No chemicals or additives
-No waste water
-No pressure loss.

7. SAFETY ISSUES OF USE OF NANOTPARTICLES

Use of NPs in water purification raises questions about the potential toxicity of nanoparticles both in the environment and in vivo after ingestion by humans. This concerns mainly non-degradable free NPs rather than fixed nanostructures, e.g. nanostructured membranes.

It is often overlooked that there are natural NPs in our environments: water and air. NPs <50 nm that enter the body are excreted. Larger NPs are trapped in biological membranes, e.g., blood-brain barrier. NPs <20 nm may enter the cells. Many concerns about safety of NPs are unfounded; several studies are ongoing to determine safety of NPs. Potential toxicity of nanoparticles, however, should be considered [9].

8. CONCLUDING REMARKS

Nanotechnology will have an impact on applications relevant to water in the areas of detection of pollution as well as purification. Nanodiagnostic technologies can provide cost-effective, rapid and large scale testing of water samples to detect heavy metal and microbial contaminations at trace levels that are not detectable by currently used routine laboratory tests.

Nanotechnologies will also play an important role in water filtration and remediation.

There is a concern about environmental effects and toxicity of nanoparticles, which is under investigation. The use of nanostructures and nanoparticles for in vitro testing and treatment of water present a negligible risk.

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НАНОТЕХНОЛОГИЈА И ВОДА

Сажетак: Овај рад разматра улогу нанобиотехнологије у проучавању биолошких система у воденом окружењу, нпр. функционалне структуре на нанометарској скали у ћелији као што је генетски материјал, мембране, ензими и молекуларне машине. Добијено знање има примјену у наномедицини. Наночестице имају практичну примјену у откривању нечистоћа воде и прочишћавања воде, што је од значаја за здравље становништва у цијелом свијету.

Кључне ријечи: вода, пречишћавање, нанобиотехнологија, биомаркери, наномедицина.