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REVIEW

Nanoparticles: pharmacological and toxicological significance

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Nanoparticles are tiny materials (<1000 nm in size) that have specific physicochemical properties different to bulk materials of the same composition and such properties make them very attractive for commercial and medical development. However, nanoparticles can act on living cells at the nanolevel resulting not only in biologically desirable, but also in undesirable effects. In contrast to many efforts aimed at exploiting desirable properties of nanoparticles for medicine, there are limited attempts to evaluate potentially undesirable effects of these particles when administered intentionally for medical purposes. Therefore, there is a pressing need for careful consideration of benefits and side effects of the use of nanoparticles in medicine. This review article aims at providing a balanced update of these exciting pharmacological and potentially toxicological developments. The classes of nanoparticles, the current status of nanoparticle use in pharmacology and therapeutics, the demonstrated and potential toxicity of nanoparticles will be discussed.
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Introduction

Nanotechnology, as defined by the United States (US) Nanotechnology Initiative, is 'the understanding and control of matter at dimensions of roughly 1–100 nanometers, where unique phenomena enable novel applications'. In the last decade, engineered nanoparticles have become an important class of new materials with several properties that make them very attractive for commercial development. In fact, they have been increasingly used for manufacturing diverse industrial items such as cosmetics or clothes and for infinite applications in electronics, aerospace and computer industry. In addition, as the need for the development of new medicines is pressing, and given the inherent nanoscale functions of the biological components of living cells, nanotechnology has been applied to diverse medical fields such as oncology and cardiovascular medicine. Indeed, nanotechnology is being used to refine discovery of biomarkers, molecular diagnostics, and drug discovery and drug delivery, which could be applicable to management of these patients. The National Institutes of Health (USA) reviewing the use of nanotechnology in human diseases introduced the term of 'nanomedicine' to describe such applications. To achieve these aims, nanotechnology strives to develop and combine new materials by precisely engineering atoms and molecules to yield new molecular assemblies on the scale of individual cells, organelles or even smaller components, providing a *personalized medicine* (Jain, 2005a, b). Personalized medicine is individualized or individual-based-therapy which allows the prescription of precise treatments best suited for a single patient (Jain, 2002).

In the last few years, several pharmacological companies won approval from the Food and Drug Administration (FDA) in the US for the use and development of nanotechnology-based drugs. Obviously, the costs of this new technology are extremely high. Today, US $9 billion are spent per year all over the world in nanotechnology (Service, 2004). Indeed, the US and Japan will spend an estimated US $6.7 billion until 2008 for research and technological development in this field. As nanotechnology is undergoing such explosive expansion in many areas, even poorer developing countries have also decided that this new technology could represent a considered investment in future economic and social well-being that they cannot ignore.

Like most new technologies, including all nascent medicine and medical devices, there is a rising debate concerning the possible side effects derived from the use of particles at the nanolevel. Because of increased use of nanotechnology, the risk associated with exposure to nanoparticles, the routes of entry and the molecular mechanisms of any cytotoxicity need to be well understood. In fact, these tiny particles are able to enter the body through the skin, lungs or intestinal tract, depositing in several organs and may cause adverse

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biological reactions by modifying the physiochemical properties of living matter at the nanolevel (Oberdörster *et al*., 2005a, b). In addition, the toxicity of nanoparticles will also depend on whether they are persistent or cleared from the different organs of entry and whether the host can raise an effective response to sequester or dispose of the particles. Recently, a number of investigators have found nanoparticles responsible for toxicity in different organs (Shvedova *et al*., 2003; Lam *et al*., 2004; Kipen and Laskin, 2005; Radomski *et al*., 2005; Chen *et al*., 2006; Donaldson *et al*., 2006; Hussain *et al*., 2006). Hence, it seems reasonable to evaluate the risk/benefits ratio for the use of nanoparticles in any technological or medical developments. In this review, we will focus upon different classes of nanoparticles, applications of nanoparticles in pharmacology, as well as the plausible side effects related to their use.

Overview of different classes of nanoparticles

Liposomes are nanoparticles comprising lipid bilayer membranes surrounding an aqueous interior. The amphilic molecules used for the preparation of these compounds have similarities with biological membranes and have been used for improving the efficacy and safety of different drugs (Hofheinz *et al*., 2005). Usually, liposomes are classified into three categories on the basis of their size and lamellarity (number of bilayers): small unilamellar vesicles or oligolamellar, large unilamellar vesicles and multilamellar vesicles. The active compound can be located either in the aqueous spaces, if it is water-soluble, or in the lipid membrane, if it is lipid-soluble.

Recently, a new generation of liposomes called 'stealth liposomes' have been developed. Stealth liposomes have the ability to evade the interception by the immune systems, and therefore, have longer half-life (Moghimi and Szebeni, 2003).

Emulsions comprise oil in water-type mixtures that are stabilized with surfactants to maintain size and shape. The lipophilic material can be dissolved in a water organic solvent that is emulsified in an aqueous phase. Like liposomes, emulsions have been used for improving the efficacy and safety of diverse compounds (Sarker, 2005).

Polymers such as polysaccharide chitosan nanoparticles have been used for some time now as drug delivery systems (Agnihotri *et al*., 2004). Recently, water-soluble polymer hybrid constructs have been developed. These are polymer–protein conjugates or polymer–drug conjugates. Polymer conjugation to proteins reduces immunogenicity, prolongs plasma half-life and enhances protein stability. Polymer–drug conjugation promotes tumour targeting through the enhanced permeability and retention effect and, at the cellular level following endocytic capture, allows lysosomotropic drug delivery (Lee, 2006).

Ceramic nanoparticles are inorganic systems with porous characteristics that have recently emerged as drug vehicles (Cherian *et al*., 2000). These vehicles are biocompatible ceramic nanoparticles such as silica, titania and alumina that can be used in cancer therapy. However, one of the main concerns is that these particles are non-biodegradable, as they can accumulate in the body, thus causing undesirable effects.

Metallic particles such as iron oxide nanoparticles (15–60 nm) generally comprise a class of superparamagnetic agents that can be coated with dextran, phospholipids or other compounds to inhibit aggregation and enhance stability. The particles are used as passive or active targeting agents (Gupta and Gupta, 2005).

Gold shell nanoparticles, other metal-based agents, are a novel category of spherical nanoparticles consisting of a dielectric core covered by a thin metallic shell, which is typically gold. These particles possess highly favourable optical and chemical properties for biomedical imaging and therapeutic applications (Hirsch *et al*., 2006).

Carbon nanomaterials include fullerenes and nanotubes. Fullerenes are novel carbon allotrope with a polygonal structure made up exclusively by 60 carbon atoms. These nanoparticles are characterized by having numerous points of attachment whose surfaces also can be functionalized for tissue binding (Bosi *et al*., 2003). Nanotubes have been one of the most extensively used types of nanoparticles because of their high electrical conductivity and excellent strength. Carbon nanotubes can be structurally visualized as a single sheet of graphite rolled to form a seamless cylinder. There are two classes of carbon nanotubes: single-walled (SWCNT) and multi-walled (MWCNT). MWCNT are larger and consist of many single-walled tubes stacked one inside the other. Functionalized carbon nanotubes are emerging as novel components in nanoformulations for the delivery of therapeutic molecules (Pagona and Tagmatarchis, 2006).

Quantum dots are nanoparticles made of semiconductor materials with fluorescent properties. Crucial for biological applications quantum dots must be covered with other materials allowing dispersion and preventing leaking of the toxic heavy metals (Weng and Ren, 2006).

Use of nanotechonology in diagnostics, pharmacology and therapeutics

Discovery of biomarkers

Nanotechnology is being applied to biomarker-based proteomics and genomics technologies. Nanoparticles can be used for qualitative or quantitative *in vivo* or *ex vivo* diagnosis by concentrating, amplifying and protecting a biomarker from degradation, in order to provide more sensitive analysis (Geho *et al*., 2004). Initial studies with magnetic nanoparticle probes coated with antibodies and single 'bar code' DNA fragments are able to amplify signals of small abundant biomolecules. This amplification is comparable to polymerase chain reaction (PCR) amplification of nucleotide sequences, and can theoretically be used to detect hundreds of protein targets at a time in patient samples. Such analysis would enable physicians to properly diagnose disease at very early stages and begin treatment before severe cellular damage, improving patient prognosis. For instance, *in vitro* streptadivin-coated fluorescent polystyrene nanoparticles have been used to detect the epidermal growth factor receptor (EGFR) in human epidermoid carcinoma cells by flow cytometry (Bhalgat *et al*., 1998). These results were

really successful as nanoparticles enhanced the sensitivity to detect EGFR compared to the conjugate streptadivin–fluorescein. In addition, a nanoparticle oligonucleotide bio-barcode assay has been used to detect small levels of the cancer marker prostate-specific antigen (PSA) in serum (Nam *et al*., 2003). The use of this new technique offers a high ratio of PCR-amplifiable DNA to labelling antibodies that can considerably enhance assay sensitivity. Therefore, a low amount of free serum PSA could be detected in patients suffering from prostate cancer or even women suffering from breast cancer with a great improvement in tumour screening and diagnosis (Nam *et al*., 2003).

Molecular diagnosis

Nowadays, imaging diagnosis is not only limited to a gross description of anatomic structures, but can also involve imaging of cellular signalling. Nanoparticles are currently being tested for molecular imaging in order to achieve a more precise diagnosis with high-quality images. In fact, contrast agents have been loaded onto nanoparticles for tumour and atherosclerosis diagnosis. The physicochemical characteristics of the nanoparticles (particle size, surface charge, surface coating and stability) allow the redirection and the concentration of the marker at the site of interest. Different nanoparticles have been used for molecular imaging with magnetic resonance images (MRI), ultrasound, fluorescence, nuclear and computed tomography imaging (Lanza and Wickline, 2003; Wickline and Lanza, 2003). For instance, gadolinium complexes have been incorporated into emulsion nanoparticles resulting in a dramatic enhancement of the signal compared to usual contrast agents (Flacke *et al*., 2001). In addition, it has been shown that ultrasmall superparamagnetic iron oxide particles enhanced the MRI signal of the thrombus in an experimental animal model developed in rabbits (Schmitz *et al*., 2001). In the last few years, an emerging area of great interest is stem cell imaging with MRI. This new technique allows treating stem cells *in vitro* with superparamagnetic nanoparticles and afterwards these cells can be injected to a specific localization in the body. The stem cells can ingest the nanoparticles by endocytosis, which results in the intracellular accumulation of nanoparticles that can exert a local effect for detection *in vivo* (Frank *et al*., 2003; Kraitchman *et al*., 2003).

Nanoparticle drug delivery systems

The use of pharmacological agents developed using classical strategies of pharmacological development is frequently limited by pharmacodynamics and pharmacokinetics problems such as low efficacy or lack of selectivity. Moreover, drug resistance at the target level owing to physiological barriers or cellular mechanisms is also encountered. In addition, many drugs have a poor solubility, low bioavailability and they can be quickly cleared in the body by the reticuloendothelial system. Furthermore, the efficacy of different drugs such as chemotherapeutical agents is often limited by dose-dependent side effects. Indeed, anticancer drugs, which usually have large volume of distribution, are toxic to both normal and cancer cells. Therefore, precise drug release into highly specified target involves miniaturizing the delivery systems to become much smaller than their targets. With the use of nanotechnology, targeting drug molecules to the site of action is becoming a reality resulting in a personalized medicine, which reduces the effect of the drug on other sites while maximizing the therapeutic effect. This goal is mainly achieved by the small size of these particles, which can penetrate across different barriers through small capillaries into individual cells. In addition, nanoparticles can be prepared to entrap, encapsulate or bind molecules improving the solubility, stability and absorption of several drugs, as well as avoiding the reticuloendothelial system, thus protecting the drug from premature inactivation during its transport. In fact, it has been shown that nanoparticles have the ability to carry various therapeutic agents including DNA, proteins, peptides, and low molecular weight compounds. Among all of them, liposome and polymer-based nanoparticulates are the most widely used nanoparticles as drug delivery systems, as these compounds are generally biodegradable, do not accumulate in the body and they are possibly risk-free (Sapra *et al*., 2005). For instance, several anticancer drugs including paclitaxel (Fonseca *et al*., 2002), 5-fluorouracil (Bhadra *et al*., 2003) and doxorubicin (Gnad-Vogt *et al*., 2005) have been successfully formulated using polymers and liposomes as drug delivery systems. However, further investigation is needed to control the drug release profile and to guide nanoparticle delivery systems to the specific target. In addition, *in vivo* studies are needed to study plausible toxicological effects derived from body accumulation of non-biodegradable nanoparticles.

Biodegradable nanoparticle-based vaccines, for oral vaccination, are also in development and may allow targeting of antigens to specific dendritic cell receptors (Foster and Hirst, 2005).

Toxicity of nanoparticles

Humans have been exposed to nanoparticles throughout their evolutionary phases; however, this exposure has been increased to a great extent in the past century because of the industrial revolution. Nanoparticles constitute a part of particulate matter (PM). Epidemiological studies have shown that urban pollution with airborne PM deriving from combustion sources such as motor vehicle and industrial emissions contributes to respiratory and cardiovascular morbidity and mortality (Pope, 2001; Peters and Pope, 2002; Brook *et al*., 2004). The respiratory risks associated with air pollution have been known as the London fog episode of 1952 (Logan, 1953).

A typical ambient PM is a highly complex mix of particles with median diameter size ranging from nm to 100 μm. Only the fraction of these particles with a mass median diameter of 2.5 μm or less is capable of depositing deep in the lung. Most of the ambient particles are submicron in size because they originate from combustion of fossil fuels or are formed by reactions from gases generated by such combustion. A typical urban atmosphere contains approximately 10^7 particles/cm^3 of air that are less than 300 nm in diameter.

Carbon in elemental form is a major component of these particles and the size of these particles is a determinant of their ability to cause systemic cardiovascular effects. Indeed, fine and ultrafine PM (from 0.1 to 2.5 μm in mass median aerodynamic diameter) that can more easily access the vasculature via inhalation are linked to cardiovascular dysfunctions (Brook *et al*., 2004), particularly in subjects with pre-existing vascular diseases.

The growing use of nanotechnology in high-tech industries is likely to become another way for humans to be exposed to intentionally generated engineered nanoparticles. Nanotechnology is also being applied in medical sciences trying to achieve a personalized medicine. However, the same properties (small size, chemical composition, structure, large surface area and shape), which make nanoparticles so attractive in medicine, may contribute to the toxicological profile of nanoparticles in biological systems. In fact, the smaller particles are, the more the surface area they have per unit mass; and this property makes nanoparticles very reactive in the cellular environment. Therefore, any intrinsic toxicity of the particle surface will be enhanced (Donaldson *et al*., 2006).

The respiratory system, blood, central nervous system (CNS), gastrointestinal (GI) tract and skin have been shown to be targeted by nanoparticles.

Respiratory system

One of the most important portals of entry and organ target for nanoparticles is the respiratory system. It is well known that lungs are easily exposed to atmospheric pollutants such as PM and many other products of thermodegradation. In this regard, combustion-derived nanoparticles have been largely studied as a possible etiologic factor for several adverse health effects, including exacerbations of airways disease as well as deaths and hospitalization from cardiovascular disease (Clancy *et al*., 2002; Donaldson *et al*., 2005). One of the main mechanisms of lung injury caused by combustion-derived nanoparticles is via oxidative stress leading to activation of different transcription factors with upregulation of proinflammatory protein synthesis (Schins *et al*., 2000). In fact, activation of mitogen-activated protein kinase and nuclear factor-kappa B signal pathways by combustion-derived nanoparticles can culminate in transcription of a number of pro-inflammatory genes such as IL-8, IL-6 and TNF-α (Yang *et al*., 1997; Steerenberg *et al*., 1998; Salvi *et al*., 2000). As nanotechnology is being applied in aerospace and computing, the release of high amounts of nanoparticles in an enclosed environment may be of great concern for airline crews and hardware engineering (Lam *et al*., 2004). In addition, aerosol therapy using nanoparticles as drug carrier systems is becoming a fashionable method to deliver therapeutic compounds (Eerikainen *et al*., 2003). It has been found that nanoparticles can induce increased lung toxicity compared to larger particles with the same chemical composition at equivalent mass concentration (Oberdörster *et al*., 2005b). In addition, it has been also shown that nanoparticles of different diameters can induce inflammatory reactions in the lungs of experimental animals (Brown *et al*., 2001; Gilmour *et al*., 2004; Dailey *et al*., 2006). In fact, a significant correlation between the surface area of nanoparticles and the induced inflammation was observed via increased oxidative stress (Brown *et al*., 2001). Interestingly, various types of nanoparticles can induce different inflammatory reactions. In fact, SWCNT has been found to be more toxic compared to other nanoparticles in inducing dose-dependent epithelioid granuloma and interstitial inflammation in lungs (Lam *et al*., 2004). In addition, nanoparticle-induced pro-inflammatory reactions have been demonstrated in several *in vitro* models of exposure (Brown *et al*., 2001, 2004). Therefore, these results indicate that nanoparticles can lead to inflammatory and granulomatous responses in lungs and this could have important implications for human risk assessment. However, as in most animal studies instillation, but not inhalation was used as a mode of delivery of nanoparticles to lungs, the relevance of pathological observations made in animals for humans remains to be established.

Nanoparticle translocation to the blood stream and central nervous system

Interestingly, nanoparticles could avoid normal phagocytic defences in the respiratory system and gain access to the systemic circulation or even to the CNS. Once inhaled and deposited, nanoparticles can translocate to extrapulmonary sites and reach other target organs by different mechanisms. The first mechanism involves passing of nanoparticles across epithelia of the respiratory tract into the interstitium and access to the blood stream directly or via lymphatic pathways, resulting in systemic distribution of nanoparticles. Berry *et al*. (1977) showed for the first time that nanoparticles can be rapidly observed in rat platelets after intratracheal instillation of particles of colloidal gold (30 nm). Nemmar *et al*. (2002) also found that inhaled (99 m)Tc-labelled carbon particles (<100 nm) pass to the blood circulation 1 min after exposure. In contrast, Brown *et al*. (2002) did not find an accumulation of the same radiolabel in the liver after exposure. However, once nanoparticles are translocated into the blood stream they could induce adverse biological effects. We have previously found that mixed carbon nanoparticles and nanotubes, both MWCNT and SWCNT, are able to induce platelet aggregation *in vitro* and, in addition accelerate the rate of vascular thrombosis in rat carotid artery (Radomski *et al*., 2005). Furthermore, it has been found that nanoparticles can directly induce cytotoxic morphological changes in human umbilical vein endothelial cells, induction of proinflammatory responses, inhibition of cell growth and reduction of endothelial nitric oxide synthase (Yamawaki and Iwai, 2006). Inhibition of cell function and induction of apoptosis have also been reported *in vitro* in kidney cells treated with SWCNT (Cui *et al*., 2005).

The translocation of nanoparticles to CNS may not only take place as a result of systemic distribution. The other mechanism involves the uptake of nanoparticles by sensory nerve endings embedded in airway epithelia, followed by axonal translocation to ganglionic and CNS structures. In addition, nanoparticles can be taken up by the nerve endings of the olfactory bulb and translocated to the CNS. It has been

found that C_{60} fullerenes can induce oxidative stress in the brain of largemouth bass via the olfactory bulb (Oberdörster, 2004). Recent studies have indicated that this translocation pathway is operational for inhaled nanoparticles. It has been shown that the exposure of rats to ^{13}C ultrafine particles (35 nm) for 6 h resulted in a significant increase of ^{13}C in the olfactory bulb on day 1 and this increase was even greater on day 7 post-exposure (Oberdörster *et al*., 2004). This result contrasts with 15-day inhalation of larger-sized MnO_2 particles in rats (1.3 and 18 μm median diameter) where no significant increase in olfactory Mn was found (Fechter *et al*., 2002). The latter observation could have been expected given that the individual axons of the fila olfactoria (forming the olfactory nerve) are only 100–200 nm in diameter. However, there are substantial differences between humans and rodents and therefore, these results should be interpreted with caution. In humans, the olfactory mucosa comprises only 5% of the total nasal mucosal surface, whereas in rats this amounts to 50%. Interestingly, human studies have shown that elevated levels of Mn could be associated with increased rate of Parkinson's disease (Olanow, 2004). Recently, it has been found that exposure of PC-12 neuroendocrine cell line to nanosized Mn induced an increase in reactive oxygen species and dopamine depletion (Hussain *et al*., 2006). However, further studies are required to evaluate whether Mn nanoparticles can induce dopamine depletion *in vivo*.

Gastrointestinal tract and skin

Other portals of nanoparticles entry in the body are GI tract and skin. Nanoparticles can be ingested into the gut by many ways. For example, nanoparticles can be ingested directly from the food, water, drugs and cosmetics, but inhaled nanoparticles can also be ingested by GI tract once they are cleared by respiratory tract (Hoet *et al*., 2004). It is known that the kinetics of particle uptake in GI tract depends on diffusion and accessibility through mucus, initial contact with enterocytes, cellular trafficking and post-translocation events. The smaller the particle diameter is the faster they could diffuse through GI secretion to reach the colonic enterocytes (Szentkuti, 1997). Following uptake by GI tract nanoparticles can translocate to the blood stream and distribute all over the body (Jani *et al*., 1990). Recently, it has been shown that Cu nanoparticles administered via oral gavage can induce adverse effects and heavy injuries in the kidney, liver and spleen of experimental mice compared to micro-Cu particles (Chen *et al*., 2006).

As with lungs, GI tract is easily exposed to stimuli that can induce an inflammatory response. Inflammatory bowel disease (IBD) that includes both ulcerative colitis and Crohn's disease (CD) is an inflammatory chronic condition whose aetiology remains still unclear. However, several lines of evidence suggest that IBD can result from a combination of genetic predisposition and environmental factors (Podolsky, 2002). It has been shown that a diet low in Ca^{2+} and exogenous microparticles alleviated the symptoms of human CD with a significant improvement in the CD activity index (Lomer *et al*., 2002). These results are particularly relevant to CD as an abnormal intestinal permeability has been found in this disease (Podolsky, 2002). However, to our knowledge, no studies published to date showed direct toxicological effects of nanoparticles in GI tract.

Nanoparticles can be also taken up by lymphatic nodes at skin level, translocating to the blood stream via lymphatic pathways (Kim *et al*., 2004). It has been found that SWCNT can induce oxidative stress and pro-inflammatory responses in human keratinocyte cells *in vitro* (Shvedova *et al*., 2003). However, no studies *in vivo* have been performed and therefore, more research is needed to investigate the effects of nanoparticles on skin.

Conclusions

The development of engineered nanoparticles with substantial biomedical significance has posed new opportunities and challenges for pharmacology and therapeutics. Nanomaterials and nanoparticles are likely to be cornerstones of innovative nanomedical devices to be used for drug discovery and delivery, discovery of biomarkers and molecular diagnostics. As nanoparticles may also exert toxicological effects, nanotoxicology has emerged as a new branch of toxicology for studying undesirable effects of nanoparticles (Donaldson *et al*., 2004; Service, 2004; Seaton and Donaldson, 2005). Therefore, development of novel nanoparticles for pharmacology, therapeutics and diagnostics must proceed in tandem with assessment of any toxicological and environmental side effects of these particles. As the bioenvironment is already polluted with nanoparticulates of PM caution should be taken to prevent and contain any environmental effects of intentionally generated nanomaterials. The diversity of engineered nanoparticles and of several possible side effects represents one of the major challenges for nanopharmacology and therapeutics.

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Conflict of interest

The authors state no conflict of interest.

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