

NANOPARTICLES COMPRISING METALLIC AND HAFNIUM OXIDE MATERIALS, PREPARATION AND USES THEREOF

The present invention relates to novel nanoparticles which can be advantageously used in the health sector as diagnostic and/or therapeutic agents. Nanoparticles of the invention comprise a metallic material at least partly covered with an oxide material, preferably an hafnium oxide material, or embedded therein. When compared to existing products, these nanoparticles offer a remarkable benefit over risk ratio. Specifically, these nanoparticles potentiate the efficiency of known metallic nanoparticles. Indeed, they retain the metal intrinsic properties and are now in addition safely usable in a mammal, in particular in a human being. The invention also relates to methods for producing said nanoparticles, to compositions containing same, and to uses thereof.

BACKGROUND

Nanotechnology offers revolutionary strategies to improve healthcare. However, as for any healthcare product, in the field of nanomedicine, the concept of expected/unexpected toxicity should be considered, from the perspective of both, what might be anticipated from the chemical and pharmacological properties of a medicinal product, and what is the knowledge in term of previous observation or documentation.

The nanoparticles toxicological issues are of most importance when designing a nanomaterial. The potential toxicity of engineered nanomaterials developed for diagnostic or therapeutic application is to be considered and encompasses phenomena such as release of toxic species into biological media, redox phenomena, electron transfer and reactive oxygen species (ROS) production. Also, adsorption of proteins on the nanoparticles surface may trigger various adverse phenomena such as change in protein conformation and subsequent loss of enzyme activity, fibrillation, or exposure to new antigenic epitopes. Pharmacokinetics is a determinant parameter of efficacy and safety prediction. Nanoparticles, which are not or only poorly degraded, after being captured by mononuclear phagocytic cells, can be entrapped in the reticuloendothelial system (RES) where they accumulate and can induce undesirable side effects.

Nanoparticle surface coating (functionalization) is perceived has an attractive approach to improve nanoparticles safety by playing different roles such as preventing nanoparticles bioreactivity and nanoparticles dissolution. Indeed, the coating of nanoparticles with a protective shell appears as an effective means of reducing their toxicity. Suitable shell

materials include biocompatible organic or inorganic substances such as PolyEthyleneGlycol compounds (PEG compounds), silica (SiO_2) and biocompatible polymers. However, these coatings are environmentally labile or degradable and an initially non-toxic material may become hazardous after shedding its coat, when the core of the nanoparticle is exposed to the body.

Cancer is a leading cause of death worldwide, accounted for 7.6 million deaths (around 13% of all deaths) in 2008. Deaths from cancer are projected to continue rising, with an estimated 12 million deaths in 2030 (WHO). Surgery, radiotherapy, and pharmaceuticals, are of central importance as anti-cancer treatment modalities, each of them can be used alone or in combination, depending on the type of cancer being treated. The choice of the therapy depends on the location and grade classification of the tumor, on the stage of the disease, as well as on the health state of the patient.

Anticancer agents that target the cell cycle and the DNA such as cytotoxics or X-rays are among the most effective in clinical use and have produced significant increase in the survival of patients with cancer when used alone or in combination with drugs that have different mechanisms of actions. They are also extremely toxic and show a narrow therapeutic window.

Therefore, there is still considerable excitement in the cancer field to modify the therapeutic ratio, aiming at efficacy and safety improvements.

Nanotechnology offers an advantageous solution to deliver therapies directly and selectively to cancerous cells. In recent years, metallic nanoparticles have shown great promise for diagnostic and therapy. Among metal nanoparticles, gold nanoparticles have been in particular proposed, especially as radiosensitizers in the context of radiotherapy (WO 2004/112590), as contrast agents in the context of diagnostic (WO2003/075961), as photothermal agents in the context of hyperthermia therapy (WO2009/091597), and as drug carriers in the context of chemotherapy (WO2002/087509).

Gold has long been and is still considered as bioinert (i.e. lack of biochemical reactivity) and thus usable *in vivo* in a mammal (WO2011/127061). This opinion is however now considered doubtful by inventors and by others.

Recent papers have questioned the inert behavior of gold nanoparticles in biological media that could reduce their use in medical applications.

Cho WS. *et al.* [Acute toxicity and pharmacokinetics of 13 nm sized PEG-coated gold nanoparticles. *Toxicology and Applied Pharmacology* 236 (2009) 16-24] have carried out an *in vivo* toxicity study using 13 nm-size gold nanoparticles coated with PEG. The PEG-5000 coated gold 13 nm nanoparticles were injected intravenously (0, 0.17, 0.85 or 4.26 mg/Kg of body weight in BALB/C mice). The nanoparticles were found to accumulate in the liver and spleen for up to 7 days. In addition, Transmission Electron Microscopy (TEM) images showed that numerous cytoplasmic vesicles and lysosomes of liver Kupffer cells and spleen macrophages contained PEG-coated gold nanoparticles. 7 days post treatment apoptosis of liver hepatocytes was significantly higher for mice given 0.85 and 4.26 mg/Kg of gold nanoparticles. Apoptotic cells was about 10% in the high dose group at seven day. Although the transient inflammatory responses were negligible for the toxicity of 13 nm PEG-coated gold nanoparticles, apoptosis of liver hepatocytes is an important adverse effect induced by treatment of 13 nm PEG-coated gold nanoparticles.

Sadauskas E. *et al.* [Protracted elimination of gold nanoparticles from mouse liver, *Nanomedicine* 5 (2009) 162-9] studied the fate of 40 nm gold nanoparticles after intravenous injections. Gold nanoparticles were injected intravenously (0.5 mL - $9 \cdot 10^{10}$ particles per mL) into adult female C57BL mice. Experimental groups were killed after 1 day, 1 month, 3 months and 6 months. The control group was killed after 1 day. The ICP-MS finding of a 9% fall in the content of gold from day 1 to 6 months revealed a protracted turnover of gold loaded Kupffer cells. AutoMetalloGraphic (AMG) staining showed that there was a decreasing number of Kupffer cells containing gold nanoparticles after a long exposure period and a significant decrease in the AMG-staining areas after 1 month. Authors believe that this reflects cannibalism between Kupffer cells. They observed unhealthy-looking large gold-containing lysosomes in animal that have survived for 3 to 6 months which may support the notion of Kupffer cell dying and being phagocytosed by surrounding Kupffer cells.

Chen YS. *et al.* [Assessment of the *in vivo* toxicity of gold nanoparticles, *Nanoscale Res. Lett.* 4(8) (2009) 858-64] have carried out an *in vivo* toxicity study using 3, 5, 12, 17, 37, 50 and 100-nm gold nanoparticles. The gold nanoparticles were injected intraperitoneally into BALB/C mice at dose of 8 mg/Kg/week. Gold nanoparticles ranging from 8 to 37 nm size induced severe sickness in mice (median survival time = 21 days). Pathological examination of the major organs of the mice in the diseased groups indicated an increase of Kupffer cells in the liver (activation of Kupffer cells suggested toxic potential for gold nanoparticles in this zone), loss of structural integrity in the lungs (structure observed similar to that of emphysema) and diffusion of white pulp in the spleen. The pathological abnormality was associated with the presence of gold nanoparticles at the diseased sites.

Inventors surprisingly discovered and now herein describe that hafnium oxide is able, when properly used in combination with metallic material, to render said metallic material, in particular gold, non toxic, without being detrimental to the metal therapeutic and diagnostic properties, thereby rendering the product of the invention advantageously usable *in vivo* in a mammal.

Inventors further believe that the claimed combination of metallic and hafnium oxide materials may be responsible for an efficient deposit of energy within the tumor structure said deposit being responsible for the dramatical enhancement of tumor destruction *in vivo* when activated by radiations when compared to standard treatments.

SUMMARY OF THE INVENTION

One embodiment of the disclosure provides a nanoparticle comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein. In a particular embodiment, the disclosed nanoparticle is a core-shell metal-oxide nanoparticle which comprises a metallic material fully covered with an hafnium oxide material or embedded therein. They also provide a composition comprising such a nanoparticle together with a pharmaceutically acceptable carrier. This composition may be a diagnostic composition or a pharmaceutical composition. Further embodiments relate to the disclosed nanoparticles for use in a mammal, preferably in a human being, as a diagnostic agent and/or as a therapeutic agent, in particular in oncology, more particularly when the nanoparticle is exposed to a radiation.

In one aspect, there is provided a core-shell metal-oxide nanoparticle comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein for use in a mammal, preferably in a human being, as a therapeutic agent, in particular in oncology, when the nanoparticle is exposed to a radiation.

In another aspect, there is provided a composition comprising a core-shell metal-oxide nanoparticle comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein as described above with a pharmaceutically acceptable carrier. In another aspect, there is provided a core-shell metal-oxide nanoparticle comprising a metallic material fully covered with an hafnium oxide material or embedded therein for use in a mammal, preferably in a human being, as a diagnostic agent when the nanoparticle is exposed to a radiation.

FIGURES

Figure 1 provides an illustration of the inventive nanoparticle structure.

Figure 1A provides an illustration of metallic crystallite or aggregate of metallic crystallites.

Figure 1B provides an illustration of core-shell metal-oxide nanoparticles which comprise a metallic material fully covered with an hafnium oxide material or embedded therein.

5 **Figure 1C** provides an illustration of nanoparticles comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein.

Figure 2 provides an illustration of the benefit over risk ratio of this inventive nanoparticle structure as compared to metallic nanoparticle deprived of hafnium oxide material, in particular in oncology, more particularly when the nanoparticle is exposed to radiations.

10 **Figure 3** provides a transmission electron microscopy picture of 60nm-sized gold nanoparticles from example 1.

Figures 4: The crystalline structure of the as prepared gold nanoparticles (example 1) is determined by electronic diffraction.

Figure 4A shows the electronic diffraction pattern of reference nanoparticles (gold nanoparticles with Cubic Face Center structure are used as reference to establish the camera constant ($L\lambda$) of the transmission electronic microscope) and of gold nanoparticles (GNPs) from example 1.

Figure 4B reports the indexation of the gold nanoparticles (from example 1), electronic diffraction pattern showing a Cubic Face Center (CFC) structure of the gold nanoparticles.

Indexing the electronic diffraction pattern consists in the following steps:

- 1) Establishing the camera constant from electronic diffraction pattern of the reference,
- 2) Measuring the ring diameter ($D_1, D_2, \dots, D_n$) of electronic diffraction pattern of the gold nanoparticles from example 1,
- 3) Calculating the d_{hkl} , using the expression $d_{hkl} = L\lambda / (D_n/2)$,
- 4) Using existing structure data base to index each ring.

Figure 5 provides pictures of the electronic diffraction pattern of core@shell Au@HfO₂ type assembly of a gold nanoparticle and hafnium oxide material from example 4.

Figure 5A shows the electronic diffraction pattern of gold@HfO₂ nanoparticles from example 4.

Figure 5B reports the indexation of the gold@HfO₂ nanoparticles (from example 4).

Indexing the electronic diffraction pattern consists in the following steps:

- 1) Establishing the camera constant from electronic diffraction pattern of the reference (Figure 4A),
- 2) Measuring the ring diameter ($D_1, D_2, \dots, D_n$) of electronic diffraction pattern of the Au@HfO₂ nanoparticles from example 4,
- 3) Calculating the d_{hkl} , using the expression $d_{hkl} = L\lambda / (D_n/2)$,
- 4) Using existing structures data base to index each ring.

Figure 6 provides a transmission electron microscopy picture of a core@shell Au@HfO₂ type assembly of gold nanoparticles and hafnium oxide material from example 4. On this cliché, it can be observed that a shell covers the gold nanoparticle surface. This shell comprises hafnium oxide material, as demonstrated by electronic diffraction.

DETAILED DESCRIPTION

The nanoparticle of the invention comprises a metallic material at least partly covered with an hafnium oxide material or embedded therein.

In the context of metal-oxide semiconductor (MOS) development for miniaturization of transistors for electronic devices, Sargentis Ch. *et al.* [Simple method for the fabrication of a high dielectric constant metal-oxide-semiconductor capacitor embedded with Pt nanoparticles, Appl. Phys. Lett. 88(073106) (2006) 1-3] developed a simple electron evaporation method to fabricate a MOS device embedded with Pt nanoparticles on its SiO₂/HfO₂ interface. The fabricated Pt nanoparticles have an average diameter of 4.9 nm and the sheet density is of 3.2×10^{12} nanoparticles/cm². This object, intended for use in the development of electronic devices, is composed of metallic nanoparticles partially embedded in an hafnium oxide layer. This object is a sheet and not a nanoparticle contrary to the object of the invention.

In a particular embodiment, the nanoparticle of the invention is a core-shell metal-oxide nanoparticle which comprises a metallic material fully covered with an hafnium oxide material or embedded therein.

In the spirit of the invention, the term "**nanoparticle**" refers, as further explained below, to products, in particular synthetic products, with a size in the nanometer range, typically between 1 nm and 500 nm.

The metallic material is typically a metallic crystallite or an aggregate of metallic crystallites.

The nanoparticle of the invention advantageously comprises one or several metallic crystallites.

In a preferred embodiment, the nanoparticle of the invention comprises several hafnium oxide crystallites and/or several hafnium oxide crystallites aggregates.

In a particular embodiment, each of the metallic material and of the hafnium oxide material consists in a crystallite or in an aggregate of crystallites.

In another particular embodiment, the nanoparticle of the invention is a core-shell metal oxide nanoparticle comprising a metallic material which is typically a metallic crystallite or an aggregate of metallic crystallites fully covered with an hafnium oxide material.

The term "**crystallite**" herein refers to a crystalline product. The size of the crystallite and its structure and composition may be analyzed from X-ray diffractogram.

The term "**aggregate of crystallites**" refers to an assemblage of crystallites strongly, typically covalently, bound to each other.

The metallic material can advantageously be selected from gold (Au), silver (Ag), platinum (Pt), palladium (Pd), tin (Sn), tantalum (Ta), ytterbium (Yb), zirconium (Zr), hafnium (Hf), terbium (Tb), thulium (Tm), cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu),

holmium (Ho), iron (Fe), lanthanum (La), neodymium (Nd), praseodymium (Pr), lutetium (Lu) and mixtures thereof. The metal is preferably selected from gold, silver, tantalum, platinum, palladium, tin, zirconium, hafnium, lutetium and iron, even more preferably from zirconium, hafnium, tantalum and gold. Most preferably the metallic material is gold or tantalum, even
5 more preferably gold.

In a particular embodiment, at least 80%, for example 85%, 86%, 87%, 88% or 89%, of the metallic material is protected from any interaction with a biological material by the hafnium oxide material. More preferably, at least 90%, typically between 90% and 98%, for example
10 95%, of the metallic material is protected from any interaction with a biological material by the hafnium oxide material.

In another particular embodiment, the nanoparticle of the invention is a core-shell metal-oxide, also identified as core@shell metal@oxide, nanoparticle which comprises a metallic
15 material fully covered with an hafnium oxide material or embedded therein.

The nanoparticle of the invention comprises a metallic material which is either at least partially covered with hafnium oxide material or fully covered with an hafnium oxide material, depending on the intended use.

For example, when the nanoparticles of the invention are used as contrast agents in the context of diagnostic or as radiosensitizers in the context of therapy, the metallic material is advantageously fully covered with an hafnium oxide material (core@shell metal@oxide nanoparticle), but when the nanoparticles of the invention are used as photothermal agents in the context of hyperthermia therapy or as drug carriers in the context of chemotherapy, the
20 metallic material is preferably at least partly covered with an hafnium oxide material.
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In a particular embodiment, in order to retain the intrinsic properties of metal materials, it may be desirable that the hafnium oxide material covering or embedding the metallic material allows the diffusion of small molecules. In particular it is important that the hafnium oxide
30 material covering or embedding the metallic material allows the passage of water or drugs, but protects the metallic material from any interaction with biological materials.

In the context of diagnostic or radiotherapy, a full coverage of the metal composition is appreciable. In the context of diagnostic, this full coverage is even preferred to optimize safe
35 use of the product.

The appropriate coverage of metallic material by the hafnium oxide material may be adjusted so that the surface area of the nanoparticles, when determined by BET (Brunauer, Emmett and Teller) surface area analysis, is equal or superior to the surface area of the nanoparticles, when typically determined by the CTAB surface area analysis.

- 5 The BET surface area analysis is based on the absorption of a gas, usually nitrogen, on the surface of the nanoparticle (the nanoparticles are in the form of powder). The BET surface area provides the "total" surface of the nanoparticle including porosity.

The CTAB surface area analysis is based on the absorption of the CetylTrimethylAmmonium Bromide (CTAB) molecule on the surface of nanoparticle (the nanoparticles are in solution).

- 10 The CTAB molecule is relatively large so that it is not adsorbed in micropores. Thus, the CTAB surface area reflects only the surface of the nanoparticle that is available for interaction with large molecules, such as interactions with biological materials. Other molecules (such as proteins) could be used otherwise in the context of the invention to estimate this nanoparticle surface area.

- 15 When the nanoparticle comprises a metallic material fully covered with an hafnium oxide material, the BET surface area is correlated to the calculated surface taking into account the shape of the nanoparticle and the relative proportion of metal and hafnium oxide materials constituting the nanoparticle, both being determined, typically by quantification of the metal and hafnium elements, using Inductively Coupled Plasma Mass Spectrometry (ICP MS)
20 analysis.

The nanoparticle's shape can be for example round, flat, elongated, polygonal, spherical, ovoid or oval, and the like. The shape can be determined or controlled by the method of production and adapted by the person of the art.

- 25 As the shape of the particles can influence their "biocompatibility", particles having a quite homogeneous shape are preferred. For pharmacokinetic reasons, nanoparticles being essentially spherical, round or ovoid in shape are thus preferred. Such a shape also favors the nanoparticle interaction with or uptake by cells. Spherical or round shape is particularly preferred.

- 30 The terms "**size of the nanoparticle**" and "**largest size of the nanoparticle**" herein refers to the "largest dimension of the nanoparticle". Transmission Electron Microscopy (TEM) can be used to measure the size of the nanoparticle. As well, Dynamic Light Scattering (DLS) can be used to measure the hydrodynamic diameter of nanoparticles in solution. These two methods may further be used one after each other to compare size measures and confirm
35 said size.

Typically, the largest dimension is the diameter of a nanoparticle of round or spherical shape, or the longest length of a nanoparticle of ovoid or oval shape.

The largest dimension of a nanoparticle as herein defined is typically between about 10 nm and about 250 nm, preferably between about 20 nm and about 100 or about 200 nm, even more preferably between about 50 nm and about 150 nm.

- 5 The metallic crystallite size (largest dimension of a metallic crystallite) is typically between about 2 nm and about 100 nm, for example between about 2 nm and 60 nm or between about 10 nm and about 50 nm. Typical examples of metallic crystallite sizes are 5, 10, 15, 30 and 50 nm.

10 The metallic crystallite aggregate size (largest dimension of a metallic crystallite aggregate) is typically between about 20 nm and about 100 nm, for example between 20 nm and 50 nm.

The hafnium oxide crystallite size (largest dimension of a hafnium oxide crystallite) is typically between about 5 nm and about 50 nm, preferably between about 2 nm and about 50 nm, for example between 5 nm and 30 nm. Typical examples of hafnium oxide crystallite sizes are 2, 5, 10, 15, 20 and 25 nm.

- 15 The hafnium oxide crystallite aggregate size (largest dimension of a hafnium oxide crystallite aggregate) is typically between about 20 nm and about 100 nm, for example between 30 nm and 70 nm.

20 The hafnium oxide crystallite size or the hafnium oxide crystallite aggregate size corresponds, in the context of the core@shell metal@oxide nanoparticle, to the thickness of the hafnium oxide shell.

In the nanoparticle of the invention, the metallic material may be advantageously coated with an agent, herein defined as a "**linker agent**", favoring adhesion between the metal and the hafnium oxide material. Adhesion in the context of the present invention means that weak
25 (hydrogen or electrostatic) or strong (covalent) interactions are established between the linker agent and the metal, and between the linker agent and the hafnium oxide material. Strong interactions are preferred. The linker agent is a compound capable of interacting, typically through covalent binding or electrostatic binding, with the metallic material surface and with the hafnium oxide material.

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The linker compound may comprise two terminal groups, R_1 and R_2 . The function of R_1 is to interact with the metallic material and the function of R_2 is to interact with the hafnium oxide material.

35 R_1 may be selected for example from a carboxylate ($R_2\text{-X-COO}^-$), a phosphonic ($R_2\text{-X-PO(OH)}_2$), a phosphoric ($R_2\text{-X-O-PO(OH)}_2$), a phosphate ($R_2\text{-X-PO}_4^{3-}$) and a thiol ($R_2\text{-X-SH}$) group.

R_2 may be selected for example from a carboxylate ($R_1-X-COO^-$), a silane ($R_1-X-Si(OR)_3$) or ($Si(OR)_4$), a phosphonic ($R_1-X-PO(OH)_2$), a phosphoric ($R_1-X-O-PO(OH)_2$), a phosphate ($R_1-X-PO_4^{3-}$) and a thiol (R_1-X-SH) group.

"X" is a chain which may be a linear or a cyclic chain containing at least one atom. The "X"

- 5 chain may be selected for example from a chain containing carbon atoms (such as an alkane chain), a chain containing carbon and oxygen atoms (such as a polyethylene oxide chain or a carbohydrate chain), a chain containing silicon atoms (such as a silicone chain), and a chain containing phosphor atoms (such as a polyphosphate chain).

- 10 In a preferred embodiment, the metallic material and/or the hafnium oxide material of the claimed nanoparticle are bound to drug molecules.

Drug molecules may interact with either the metallic material and/or the hafnium oxide material via for instance hydrogen interactions, electrostatic interactions, or covalent bonding. The drug molecule may further comprise a cleavable linkage allowing the release of

15 the drug molecule when the nanoparticle is exposed to a specific stimulus.

Such a cleavable linkage can be selected for example from a disulfide linkage or a pH-sensitive linkage such as a hydrazone linkage.

The specific stimulus capable of cleaving the linkage may be an environmental stimulus or a physical stimulus, typically an external physical stimulus. An environmental stimulus capable

20 of cleaving the linkage may be for example the pH, capable of cleaving the pH-sensitive linkage or a reducing environment, capable of reducing the disulfide linkage. The physical stimulus capable of cleaving the linkage may be for example a radiation, in particular an ionizing radiation.

- 25 Drug molecules in the context of the present invention include any compound with therapeutic or prophylactic effects. It can be a compound that affects or participates for example to tissue growth, cell growth or cell differentiation. It can also be a compound that is capable to induce a biological action such as an immune response.

- A non-limiting list of examples includes antimicrobial agents (including antibacterial, in particular antibiotics, antiviral agents and anti-fungal agents); anti-tumor agents, in particular anticancer chemotherapeutic agents such as cytostatic(s), cytotoxic(s), and any other biological or inorganic product intended to treat cancer such as a therapeutic nucleic acid, in particular a micro RNA (miRNA), a short-hairpin RNA (shRNA) and/or a small interfering RNA (siRNA). The drug can also be a prodrug in the context of the present invention. Any
- 35 combination of drug molecules of interest may further be used.

In another embodiment, a nanoparticle wherein the hafnium oxide material is coated with a biocompatible material selected from an agent exhibiting stealth property, an agent allowing interaction with a biological target, and a combination thereof, is herein described.

- 5 The Enhanced Permeation and Retention ("EPR") effect is known to be responsible for passive accumulation of the nanoparticles into the tumor mass, after a given time following their injection by the intravenous route (one possible route of administration). It has indeed been observed that the tumor vessels are quite distinct from normal capillaries and that their vascular "leakiness" encourages selective extravasation of nanoparticles not usual in normal
10 tissues. The lack of effective tumor lymphatic drainage prevents clearance of the penetrant nanoparticles and promotes their accumulation. The present nanoparticles are thus able to successfully target primary as well as metastatic tumors after intravenous administration.

- In a preferred embodiment, the hafnium oxide material of the claimed nanoparticles can be
15 coated with a biocompatible material selected from an agent exhibiting stealth property. Indeed, when the nanoparticles of the present invention are administered to a subject via the intravenous (IV) route, a biocompatible coating with a material selected from an agent exhibiting stealth property is particularly advantageous to optimize the biodistribution of the nanoparticles. Said coating is responsible for the so called "stealth property" of the
20 nanoparticle.

- Agent exhibiting stealth properties may be an agent displaying a steric group. Such a group may be selected for example from polyethylene glycol (PEG); polyethylenoxide; polyvinylalcohol; polyacrylate; polyacrylamide (poly(N-isopropylacrylamide)); polycarbamide; a biopolymer; a polysaccharide such as dextran, xylan and cellulose; collagen; a switterionic
25 compound such as polysulfobetain; etc.

- In another preferred embodiment, the hafnium oxide material of the claimed nanoparticles can be coated with a biocompatible material selected from an agent allowing interaction with a biological target. Such agent can typically bring a positive or a negative charge on the
30 nanoparticles surface. This charge can be determined by zeta potential measurements, typically performed on nanoparticles suspensions the concentration of which vary between 0.2 and 10 g/L, the nanoparticles being suspended in an aqueous medium with a pH comprised between 6 and 8.

- An agent forming a positive charge on the nanoparticle surface can be for example
35 aminopropyltriethoxysilane or polylysine. An agent forming a negative charge on the nanoparticle surface can be for example a phosphate (for example a polyphosphate, a

metaphosphate, a pyrophosphate, etc.), a carboxylate (for example citrate or dicarboxylic acid, in particular succinic acid) or a sulphate.

A full biocompatible coating of the nanoparticle or aggregate may be advantageous, in particular in the intravenous (IV) context, in order to avoid interaction of the particle surface with any recognition element (macrophage, opsonins, etc.). The "full coating" implies the presence of a very high density of biocompatible molecules able to create at least a complete monolayer on the surface of the particle.

The biocompatible coating allows in particular the nanoparticle stability in a fluid, such as a physiological fluid (blood, plasma, serum, etc.), any isotonic media or physiologic medium, for example media comprising glucose (5%) and/or NaCl (0.9 %), which is required for a pharmaceutical administration.

Stability may be confirmed by dry extract quantification measured on a nanoparticle suspension prior and after filtration, typically on a 0.22 or 0.45 μm filter.

Advantageously, the coating preserves the integrity of the particles *in vivo*, ensures or improves the biocompatibility thereof, and facilitates an optional functionalization thereof (for example with spacer molecules, biocompatible polymers, targeting agents, proteins, etc.).

A particular nanoparticle according to the present invention can further comprise a targeting agent allowing its interaction with a recognition element present on the target cell. Such a targeting agent typically acts once the nanoparticles are accumulated on the target site. The targeting agent can be any biological or chemical structure displaying affinity for molecules present in the human or animal body. For instance it can be a peptide, oligopeptide or polypeptide, a protein, a nucleic acid (DNA, RNA, siRNA, tRNA, miRNA, etc.), a hormone, a vitamin, an enzyme, the ligand of a molecule expressed by a pathological cell, in particular the ligand of a tumor antigen, hormone receptor, cytokine receptor or growth factor receptor. Said targeting agents can be selected for example in the group consisting in LHRH, EGF, a folate, anti-B-FN antibody, E-selectin/P-selectin, anti-IL-2R α antibody, GHRH, etc.

The nanoparticles of the invention can be administered by different routes such as local (intra-tumoral (IT) in particular), subcutaneous, intra venous (IV), intra-dermic, intra-arterial, airways (inhalation), intra peritoneal, intra muscular and oral route (*per os*). The nanoparticles can further be administered in an intracavity such as the virtual cavity of tumor bed after tumorectomy.

Repeated injections or administrations of nanoparticles can be performed, when appropriate.

Another particular object of the invention relates to a pharmaceutical composition comprising nanoparticles such as defined hereinabove, preferably together with a pharmaceutically acceptable carrier or vehicle.

Another particular object of the invention relates to a diagnostic or imaging composition
5 comprising nanoparticles such as defined hereinabove, preferably together with a physiologically acceptable carrier or vehicle.

The compositions can be in the form of a solid, liquid (particles in suspension), aerosol, gel, paste, and the like. Preferred compositions are in liquid or gel form. Particularly preferred compositions are in liquid form.

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The carrier which is employed can be any classical support for this type of application, such as for example saline, isotonic, sterile, buffered solutions, and the like. They can also comprise stabilizers, sweeteners, surfactants, polymers and the like. They can be formulated for example as ampoules, aerosol, bottles, tablets, capsules, by using known techniques of
15 pharmaceutical formulation.

In the herein described compositions, appropriate or desirable concentrations of nanoparticles are comprised between about 10^{-3} mg of nanoparticles / gram of tumor and about 100 mg of nanoparticles / gram of tumor, in particular between about 5 and about 50
20 mg of nanoparticles / gram of tumor. These concentrations apply whatever the route of administration.

In the herein described compositions, appropriate or desirable concentrations of nanoparticles are comprised between about 10^{-3} mg of nanoparticles / mL of volume of the virtual cavity left following tumorectomy and about 100 mg of nanoparticles / mL of volume of the virtual cavity left following tumorectomy, in particular between about 5 mg and about 50
25 mg of nanoparticles / mL of volume of the virtual cavity left following tumorectomy. These concentrations apply whatever the route of administration.

Generally, the compositions in liquid or gel form comprise between 0.05 g/L and 400 g/L of nanoparticles, 0.05 g/L and 150 g/L, preferably at least 10 g/L, 20 g/L, 40 g/L, 45 g/L, 50 g/L, 55 g/L, 60 g/L, 80 g/L, 100 g/L, 150 g/L, 200 g/L, 250 g/L, 300 g/L or 350 g/L.

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Dry extract is ideally measured following a drying step of the suspension comprising the nanoparticles.

The compositions, particles and aggregates of the invention can be used in many fields, particularly in human or veterinary medicine.
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Nanoparticles and compositions according to the invention, as herein described, are preferably for use in a mammal, even more preferably in a human being, as a diagnostic agent, typically when the nanoparticle is exposed to a radiation, and/or as a therapeutic agent, in particular in oncology, preferably when the nanoparticle is exposed to radiations, in particular ionizing radiations.

The terms "radiation" refers to ionizing and non-ionizing radiation. Non-ionizing radiation includes radio waves, microwaves, infrared, and visible light. Ionizing radiation includes typically ultraviolet light, X-rays and gamma-rays.

The terms "treatment" and "therapy" refer to any action performed to correct abnormal functions, to prevent diseases, to improve pathological signs, such as in particular a reduction in the size or growth of an abnormal tissue, in particular of a tumor, a control of said size or growth, a suppression or destruction of abnormal cells or tissues, a slowing of disease progression, a disease stabilization with delay of cancer progression, a reduction in the formation of metastases, a regression of a disease or a complete remission (in the context of cancer for example), etc.

While not intending to be bound by any particular theory, inventors believe that the claim combination of metallic and hafnium oxide materials may be responsible, in the context of therapy, for the efficient deposit of energy within the tumor structure, when the nanoparticles are activated by radiations.

Typically, following intravenous injection, the Enhanced Permeation and Retention ("EPR") effect will be responsible for passive accumulation of the nanoparticles at the tumor site.

Upon nanoparticles activation by radiations, the deposit of energy will enhance tumor perfusion and consequently further favor the nanoparticles intratumor penetration. The enhance nanoparticle intratumor penetration (nanoparticles intratumor bioavailability) will potentiate the therapeutic activity of the inventive nanoparticles (Figure 2).

Hence a particular object of the invention is based on the use of a nanoparticle according to the present invention to prepare a pharmaceutical composition intended to alter, destroy or eliminate target cells in an animal, when said cells are exposed to radiations, in particular to ionizing radiations, and on the corresponding methods.

The target cells can be any pathological cells, that is to say, cells involved in a pathological mechanism, for example proliferative cells, such as tumor cells, stenosing cells (fibroblast/smooth muscle cells), or immune system cells (pathological cell clones). A

preferred application is based on the treatment (for example the destruction or functional alteration) of malignant cells or tissue.

Another particular embodiment of the invention relates to the use of compositions or nanoparticles such as defined hereinabove for producing a pharmaceutical composition for the treatment of cancer, when nanoparticles are exposed to radiations, in particular to ionizing radiations.

The present disclosure further encompasses the use of the nanoparticles and/or compositions of the invention to prevent or treat a cancer or to alleviate the symptoms of a cancer in an animal, when cells are exposed to radiations, in particular to ionizing radiations.

Classical cancer management systematically implies the concurrence of multimodality treatments (combination of radiotherapy and chemotherapy for example).

The herein described nanoparticles submitted to radiations, in particular in the context of radiotherapy, can be used in association with a different cancer therapy protocol. Such a protocol can be selected from the group consisting of surgery, radiosurgery, chemotherapy, a treatment comprising administration of cytostatic(s), cytotoxic(s), a targeted therapy, a vaccine, radionuclides, in particular immunoradionuclides, and any other biological or inorganic product intended to treat cancer.

The invention can be used to treat any type of malignant tumor such as haematological tumors or malignancies, and solid tumors, in particular of epithelial, neuroectodermal or mesenchymal origin. In addition, nanoparticles can be used to treat a premalignant lesion or a specific benign disease for which radiation therapy is classically used and/or indicated.

The invention is applicable, in the context of therapy, to primary tumors, or secondary invasions, loco-regional or distant metastases, as well as in the context of prophylaxis in order to avoid secondary malignant central nervous system involvement such as the observed invasions (metastasis) from melanoma, lung cancer, kidney cancer, breast cancer, etc.

The nanoparticles can be used at any time throughout the anticancer treatment period. They can be administered for example as a neoadjuvant (before surgical intervention for cancer exeresis) or as an adjuvant (after surgery).

The nanoparticles can also be used for advanced tumors which cannot be surgically removed.

The nanoparticles herein described are in particular intended to be used to treat cancer where radiotherapy is a classical treatment. Such cancer may be selected in particular from the group consisting of skin cancer, including malignant neoplasms associated to AIDS, melanoma; central nervous system tumors including brain, stem brain, cerebellum, pituitary, spinal canal, eye and orbit; head and neck tumors; lung cancers; breast cancers; gastrointestinal tumors such as liver and hepatobiliary tract cancers, colon, rectum and anal cancers, stomach, pancreas, oesophagus cancer; male genitourinary tumors such as prostate, testis, penis and urethra cancers; gynecologic tumors such as uterine cervix, endometrium, ovary, fallopian tube, vagina and vulvar cancers; adrenal and retroperitoneal tumors; sarcomas of bone and soft tissue regardless the localization; lymphoma; myeloma; leukemia; and pediatric tumors such as Wilm's tumor, neuroblastoma, central nervous system tumors, Ewing's sarcoma, etc.

The nanoparticles herein described can further now be used in the context of radiotherapy where their use allows a decrease of the dose of radiotherapy while keeping its efficiency in destroying tumor cells.

Under the effect of ionizing radiations, in particular X-Rays, gamma-rays, radioactive isotopes and/or electron beams, the nanoparticles are excited and produce electrons and/or high energy photons. Those electrons and/or high energy photons emitted after ionization will be responsible for direct and/or indirect cells damages, via free radicals generation, and ultimately for cells destruction, resulting in a better outcome for the patient.

Depending on the energy of ionizing radiations, the nanoparticles can thus enable the destruction of tissues and/or, simply, visualization for imaging and/or for diagnostics purposes.

The particles can be excited within a large range of total dose of radiation.

Amounts and schedules (planning and delivery of irradiations in a single dose, or in the context of a fractionated or hyperfractionated protocol, etc.) is defined for any disease/anatomical site/disease stage patient setting/patient age (children, adult, elderly patient), and constitutes the standard of care for any specific situation.

The irradiation can be applied at any time after administration of the nanoparticles, on one or more occasions, by using any currently available system of radiotherapy or radiography.

As indicated previously, appropriate radiations or sources of excitation are preferably ionizing radiations and can advantageously be selected from the group consisting of X-Rays,

gamma-Rays, electron beams, ion beams and radioactive isotopes or radioisotopes emissions. X-Rays is a particularly preferred source of excitation.

Ionizing radiations are typically of about 2 KeV to about 25 000 KeV, in particular of about 2 KeV to about 6000 KeV (LINAC source), or of about 2 KeV to about 1500 KeV (such as a cobalt 60 source).

In general and in a non-restrictive manner, the following X-Rays can be applied in different cases to excite the particles:

- Superficial X-Rays of 2 to 50 keV : to excite nanoparticles near the surface (penetration of a few millimeters);
- X-Rays of 50 to 150 keV: in diagnostic but also in therapy;
- X-Rays (ortho voltage) of 200 to 500 keV which can penetrate a tissue thickness of 6 cm;
- X-Rays (mega voltage) of 1000 keV to 25,000 keV. For example the excitation of nanoparticles for the treatment of prostate cancer can be carried out via five focused X-Rays with an energy of 15,000 keV.

Radioactive isotopes can alternatively be used as an ionizing radiation source (named as curietherapy or brachytherapy). In particular, Iodine I^{125} ($t_{1/2} = 60.1$ days), Palladium Pd^{103} ($t_{1/2} = 17$ days), Cesium Cs^{137} and Iridium Ir^{192} can advantageously be used.

Charged particles such as proton beams, ions beams such as carbon, in particular high energy ion beams, can also be used as a ionizing radiation source and/or neutron beams.

Electron beams may also be used as a ionizing radiation source with energy comprised between 4 MeV and 25 MeV.

Specific monochromatic irradiation source could be used for selectively generating X-rays radiation at an energy close to or corresponding to the desired X-ray absorption edge of the atoms constituting the metallic material or of the hafnium element.

Preferentially sources of ionizing radiations may be selected from Linear Accelerator (LINAC), Cobalt 60 and brachytherapy sources.

In the field of diagnostics, the inventive nanoparticles can be used as contrast agents, for detecting and/or visualizing any type of tissue. Thus, an object of the invention relates to the use of nanoparticles, such as defined hereinabove, for the detection and/or the visualization of cells, tissues or organs, the nanoparticles being bioinert as such and activable (i.e. usable as diagnostic agents) when exposed to radiations generated in particular by radiography devices.

The present disclosure further provides kits comprising any one of the herein-described nanoparticles or compositions as well as combinations thereof. Typically, the kit comprises at least nanoparticles according to the present invention, typically a suspension thereof.

- 5 Generally, the kit further comprises one or more containers filled with one or more of the ingredients herein described of the compositions of the invention. Associated with such container(s), a labeling notice providing instructions for using the products can be provided for using the nanoparticles, or compositions according to the present methods.
- 10 Other aspects and advantages of the invention will become apparent in the following examples, which are given for purposes of illustration and not by way of limitation.

EXAMPLES

15 **EXAMPLE 1: Synthesis of gold crystallites**

Gold crystallites are obtained by reduction of gold chloride (HAuCl_4) with sodium citrate in aqueous solution. Protocol was adapted from G. Frens Nature Physical Science 241 (1973) 21.

- 20 In a typical experiment, HAuCl_4 solution is heated to boiling. Subsequently, sodium citrate solution is added. The resulting solution is maintained under boiling for an additional period of 5 minutes.

The crystallite size may be adjusted by carefully modifying the citrate versus gold precursor ratio (see Table 1).

- 25 The as prepared gold crystallites suspensions are then washed with water and concentrated using an ultrafiltration device (Amicon stirred cell model 8400 from Millipore) with a 30 kDa cellulose membrane, at least to a gold concentration equal or superior to 1g/L. The gold content is determined by ICP-MS.

- The resulting suspensions are ultimately filtered through a 0.22 μm cutoff membrane filter (PES membrane from Millipore) under laminar hood and stored at 4°C.
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The gold crystallite size is determined using Transmission Electronic Microscopy (TEM) by counting more than 200 particles. Histograms are established and mean and standard deviation are reported.

- 35 **Table 1: Typical gold crystallites obtained from reduction of gold chloride with sodium citrate. The size may be adjusted by modifying the citrate versus gold precursor ratio.**

Samples	Crystallite size	Synthesis	
		Citrate	HAuCl ₄
Gold crystallite-15	15±2 nm	20 mL 30 mM	500 mL 0.25 mM
Gold crystallite-30	32±10 nm	7.5 mL 40 mM	500 mL 0.25 mM
Gold crystallite-60	60±10 nm	2 mL 85 mM	500 mL 0.25 mM

EXAMPLE 2: Nanoparticles suspension comprising a gold material at least partially covered with hafnium oxide material

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A Tetramethylammonium hydroxide (TMAOH) solution is added to hafnium chloride (HfCl₄) solution. Addition of TMAOH solution is performed until the pH of the final suspension reaches a pH comprised between 7 and 13. A white precipitate is obtained.

Gold crystallites suspension from example 1 is slowly added to the white precipitate under vigorous mixing.

The resulting precipitate is further transferred in an autoclave and heated at a temperature comprised between 100 °C and 300 °C. After cooling, the suspension is washed with water.

A peptization step is performed in order to get a stable suspension of nanoparticles comprising gold material at least partly embedded in hafnium oxide material.

Suspension of sodium hexametaphosphate is then added to the peptized solution and the pH of the suspension is adjusted to a pH comprised between 6 and 8.

EXAMPLE 3: Gold nanoparticles coated with a "linker agent" favoring adhesion between the metal and the hafnium oxide material

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A 10 mL suspension of gold nanoparticles of 60nm mean diameter at a concentration [Au]=0.1g/L was mixed with a solution of mercaptopropyltriethoxysilane (MPTS) in ethanol (EtOH). pH of the as-obtained suspension was adjusted to $8 \leq \text{pH} \leq 10$ with a basic solution. The mixture was then heated in a stove at a temperature $T \geq 90^\circ\text{C}$.

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EXAMPLE 4: Nanoparticles comprising gold coated with a "linker agent" at least partially covered with or fully embedded in hafnium oxide material: a core@shell Au@HfO₂ type assembly

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Suspensions of gold nanoparticles coated with MPTS as a "linker agent" from example 3 were used. Typically, 500 μ L of a solution of hafnium chloride (HfCl_4) at 20g/L was slowly added to 5mL of a suspension of gold nanoparticles coated with MPTS as a linker agent. The pH rapidly decreased to $\text{pH} < 2$. It was then adjusted to $2 \leq \text{pH} \leq 4$, $4 < \text{pH} < 8$ or to $8 \leq \text{pH} \leq 10$ with a basic solution. Acidic, neutral or basic pH allows modulating the crystallinity of the hafnium oxide crystallites. The as-obtained solutions were then incubated in a stove, first at a temperature $50^\circ\text{C} \leq T \leq 100^\circ\text{C}$, then at $T \geq 100^\circ\text{C}$ in an autoclave. A core@shell Au@HfO_2 nanoparticle structure is obtained as shown by TEM (Figure 6).

EXAMPLE 5 : Electronic diffraction patterns of nanoparticles comprising gold at least partially covered with or fully embedded in hafnium oxide material (Au@HfO_2)

In order to determine the crystalline structure of the as prepared nanoparticles, electronic diffraction was performed on two samples: gold nanoparticles from example 1 (Figure 4) and Au@HfO_2 type assembly of gold nanoparticles and hafnium oxide material from example 4 (Figure 5).

For gold nanoparticles from example 1, the crystalline structure found matches with a CFC structure with a lattice parameter $a_{\text{experimental}} = 3.984\text{\AA}$ (Figure 4).

For a core@shell Au@HfO_2 type assembly of gold nanoparticles and hafnium oxide material from example 4 (Figure 5), the electronic diffraction pattern shows points corresponding to interreticular distances of gold CFC crystalline structure: d_{111} , d_{200} , d_{220} and d_{311} . An additional diffraction pattern is observed. Indexation shows three main interreticular distances: 2.798 $\text{\AA}$, 1.599 $\text{\AA}$ and 1.316 $\text{\AA}$, which can be attributed to diffraction plans of the HfO_2 monoclinic crystalline structure with $a=5.12\text{\AA}$, $b=5.18\text{\AA}$, $c=5.25\text{\AA}$ and $\beta=98^\circ$ (reference: HfO_2 00-006-0318) and which corresponds to d_{111} , d_{311} and d_{223} , respectively.

CLAIMS

1. Core-shell metal-oxide nanoparticle comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein for use in a mammal, preferably in a human being, as a therapeutic agent, in particular in oncology, when the nanoparticle is exposed to a radiation.
2. Core-shell metal-oxide nanoparticle according to claim 1, wherein the metallic material is selected from gold (Au), silver (Ag), platinum (Pt), palladium (Pd), tin (Sn), tantalum (Ta), ytterbium (Yb), zirconium (Zr), hafnium (Hf), terbium (Tb), thulium (Tm), cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), holmium (Ho), iron (Fe), lanthanum (La), neodymium (Nd), praseodymium (Pr), lutetium (Lu) and mixtures thereof.
3. Core-shell metal-oxide nanoparticle according to claim 1 or 2, wherein at least 80% of the metallic material is protected from any interaction with a biological material by the hafnium oxide material.
4. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the metallic material is a metallic crystallite or an aggregate of metallic crystallites.
5. Core-shell metal-oxide nanoparticle according to claim 4, wherein the nanoparticle comprises one or several metallic crystallites.
6. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the nanoparticle comprises several hafnium oxide crystallites or hafnium oxide crystallites aggregates.
7. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the largest dimension of a metallic crystallite is between about 2 nm and about 100 nm and the largest dimension of a hafnium oxide crystallite is between about 5 nm and about 50 nm.

8. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the largest dimension of a nanoparticle is between 10 nm and 250 nm.

9. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the metallic material is coated with an agent favoring adhesion between the metal and the hafnium oxide material.

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10. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the metallic material and/or the hafnium oxide material are bonded with drug molecules.

5 11. Core-shell metal-oxide nanoparticle according to claim 10, wherein each drug molecule comprises a cleavable portion allowing the release of the drug molecule when the nanoparticle is exposed to a specific stimulus.

10 12. Core-shell metal-oxide nanoparticle according to anyone of preceding claims, wherein the hafnium oxide material is coated with a biocompatible material selected from an agent exhibiting stealth property, an agent allowing interaction with a biological target, and a combination thereof.

15 13. Composition comprising a core-shell metal-oxide nanoparticle comprising a metallic material at least partly covered with an hafnium oxide material or embedded therein as described in anyone of preceding claims together with a pharmaceutically acceptable carrier.

20 14. Core-shell metal-oxide nanoparticle comprising a metallic material fully covered with an hafnium oxide material or embedded therein for use in a mammal, preferably in a human being, as a diagnostic agent when the nanoparticle is exposed to a radiation.

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