Pharmaceutical Preparation

Background

The present invention relates to the field of endoradionuclide therapy, and in particular to alpha-endoradionuclide therapy. More specifically the present invention relates to the safety and efficacy of preparations for use in endoradionuclide therapy, to such preparations and to methods for their preparation, treatment and safe storage.

The basic principle of endo-radionuclide therapy is the selective destruction of undesirable cell types, e.g. for cancer therapy. Radioactive decay releases significant amounts of energy, carried by high energy particles and/or electromagnetic radiation. The released energy causes cytotoxic damage to cells, resulting in direct or indirect cell death. Obviously, to be effective in treating disease, the radiation must be preferentially targeted to diseased tissue such that this energy and cell damage primarily eliminates undesirable tumour cells, or cells that support tumour growth.

Certain beta-particle emitters have long been regarded as effective in the treatment of cancers. More recently, alpha-emitters have been targeted for use in anti-tumour agents. Alpha-emitters differ in several ways from beta-emitters, for example, they have higher energies and shorter ranges in tissues. The radiation range of typical alpha-emitters in physiological surroundings is generally less than 100 μm, the equivalent of only a few cell diameters. This relatively short range makes alpha-emitters especially well-suited for treatment of tumours including micrometastases, because when they are targeted and controlled effectively, relatively little of the radiated energy will pass beyond the target cells, thus minimising damage to the surrounding healthy tissue. In contrast, a beta-particle has a range of 1 mm or more in water.

The energy of alpha-particle radiation is high compared to that from beta-particles, gamma rays and X-rays, typically being 5-8 MeV, or 5 to 10 times higher than from beta-particle radiation and at least 20 times higher than from gamma radiation. The provision of a very large amount of energy over a very short distance gives alpha-radiation an exceptionally high linear energy transfer (LET) when compared to beta- or gamma-radiation. This explains the exceptional cytotoxicitiy

of alpha-emitting radionuclides and also imposes stringent demands on the level of control and study of radionuclide distribution necessary in order to avoid unacceptable side effects due to irradiation of healthy tissue.

Thus, while very potent, it is important to deliver the alpha-emitting radionuclides to the tumour with little or no uptake in non-disease tissues. This may be achieved analogously to what has been shown when delivering the beta-emitting radionuclide yttrium-90 (Y-90) using a monoclonal antibody conjugated with the chelating molecule DTPA as a carrier, i.e. the clinically used radiopharmaceutical Zevalin® (Goldsmith, S.J, Semin. Nucl. Med. 40: 122-35. Radioimmunotherapy of lymphoma: Bexxar and Zevalin.). Thus, a complex of the radionuclide and the carrier-chelator conjugate is administered. Besides full length antibodies of different origins, other types of proteinaceous carriers have been described, including antibody fragments (Adams et al., A single treatment of yttrium-90-labeled CHX-A"-C6.5 diabody inhibits the growth of established human tumor xenografts in immunodeficient mice. Cancer Res. 64: 6200-8, 2004), domain antibodies (Tijink et al., Improved tumor targeting of anti-epidermal growth factor receptor Nanobodies through albumin binding: taking advantage of modular Nanobody technology. Mol. Cancer Ther. 7: 2288-97, 2008), lipochalins (Kim et al., High-affinity recognition of lanthanide(III) chelate complexes by a reprogrammed human lipocalin 2. J. Am. Chem. Soc. 131: 3565-76, 2009), affibody molecules (Tolmachev et al., Radionuclide therapy of HER2-positive microxenografts using a ^{177}Lu-labeled HER2-specific Affibody molecule. Cancer Res. 15:2772-83, 2007) and peptides (Miederer et al., Preclinical evaluation of the alpha-particle generator nuclide ^{225}Ac for somatostatin receptor radiotherapy of neuroendocrine tumors. Clin. Cancer Res. 14:3555-61, 2008).

Decomposition or “decay” of many pharmaceutically relevant alpha emitters results in formation of "daughter" nuclides which may also decay with release of alpha emission. Decay of daughter nuclides may result in formation of a third species of nuclides, which may also be alpha emitter, leading to a continuing chain of radioactive decay, a “decay chain”. Therefore, a pharmaceutical preparation of a pharmaceutically relevant alpha emitter will often also contain decay products that are themselves alpha emitters. In such a situation, the preparation will contain a mix

of radionuclides, the composition of which depends both on the time after preparation and the half-lives of the different radionuclides in the decay chain.

The very high energy of an alpha-particle, combined with its significant mass, results in significant momentum being imparted to the emitted particle upon nuclear decay. As a result, when the alpha particle is released an equal but opposite momentum is imparted to the remaining daughter nucleus, resulting in "nuclear recoil". This recoil is sufficiently powerful to break most chemical bonds and force the newly formed daughter nuclide out of a chelate complex where the parent nuclide was situated when decomposing. This is highly significant where the daughter nucleus is itself an alpha-radiation emitter or is part of a continuing chain of radioactive decay.

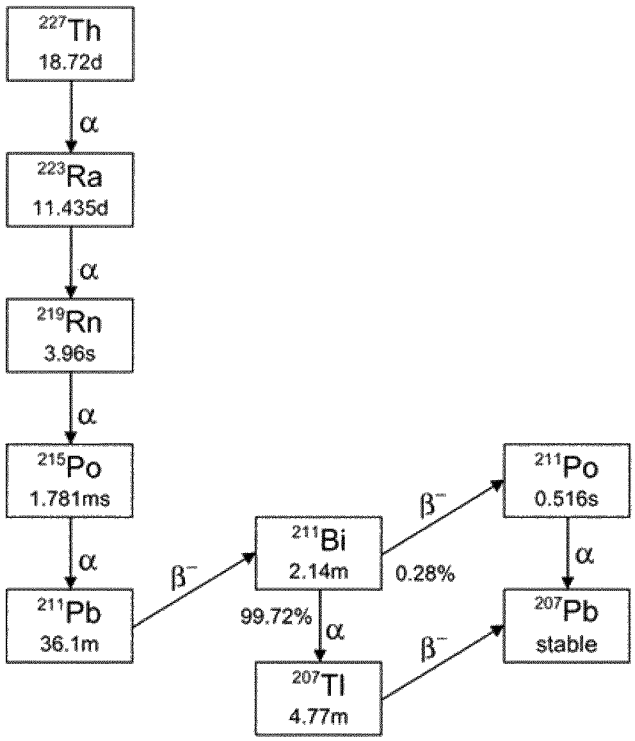
Due to the recoil effects discussed above and due to the change in chemical nature upon radioactive decay, the daughter nuclides thus formed from radioactive decay of the initially incorporated radionuclide may not complex with the chelator. Therefore, in contrast to the parent nuclide, daughter nuclides and subsequent products in the decay chain may not be attached to the carrier. Thus, storage of an alpha-emitting radioactive pharmaceutical preparation will typically lead to accumulation “ingrowth” of free daughter nuclides and subsequent radionuclides in the decay chain, which are no longer effectively bound or chelated. Unbound radioisotopes are not controlled by the targeting mechanisms incorporated into the desired preparation and thus it is desirable to remove the free daughter nuclides prior to dose administration to patients.

Since the radioisotope thorium-227 will be generated and purified in a dedicated production facility, a certain storage period between formation, transportation, complexation and administration of the dose is inevitable, and it is desirable that the pharmaceutical preparation be as free from daughter nuclides as possible as is practicable. A significant problem with past methods has been to administer a reproducible composition of a targeted alpha-radionuclide, which does not contain variable amounts of non-targeted alpha-radionuclides (e.g. free daughter nuclides) in relation to the targeted amount. It is further desirable to reduce the exposure of organic components such as binding/targeting moieties and/or ligands to ionising alpha-radiation. Removal of free radioisotopes from solution contributes to

reducing the radiolysis of such components and thus helps to preserve the quality of the pharmaceutical preparation or precursor solution.

Although the decay of the desired nuclide during the storage and transportation period can be calculated and corrected for, this does not avoid the build-up of un-targeted daughter products which can render the composition more toxic and/or reduce the safe storage period and/or alter the therapeutic window in undesirable ways. In addition, it would thus be of benefit for the compositions to be as free from daughter nuclides as possible and that a process for drug product dose manufacture is established which ensures the injected dose has a composition which can be assured as being acceptably safe.

The events following decomposition of thorium-227 may be considered as an illustration of the challenge.



Decay chain of thorium-227

With a half-life of about 18.7 days thorium-227 decomposes into radium-223 upon release of an alpha-particle. Radium-223 in turn has a half-life of about 11.4 days, and decomposing into radon-219, giving rise to polonium-215, which gives

rise to lead-211. Each of these steps gives rise to alpha-emission and the half-lives of radon-219 and polonium-215 are less than 4 seconds and less than 2 milliseconds, respectively. The end result is that the radioactivity in a freshly prepared solution of e.g. chelated thorium-227 will increase over the first 19 days, and then start to decrease. Clearly the amount of thorium-227 available for being targeted to a tumor is constantly decreasing, and thus the fraction of the total radioactivity deriving from thorium-227 is dropping during these 19 days, when an equilibrium situation is reached. If daughter nuclides could be specifically removed in a simple procedure, only the amount of thorium-227 (e.g. complexed to the biomolecule carrier) would have to be considered, and the therapeutic window – the relation between therapeutic effect and adverse effects would be unrelated to the time of storage prior to removal of the daughter isotopes. This may be continuous during the storage of the product or may be shortly before administration, such as at the fime of formulation and complexation leading to drug product.

Thus, there is considerable ongoing need for improved radiotherapeutic compositions (particularly for alpha-emitting radionuclides), and procedures for making a solution ready for injection whose biological effects may be reproducibly assessed, without having to consider ingrown radionuclides formed in the radioactive decay chain. Furthermore, there is a need for radiotherapeutic methods and kits allowing facile preparation of a final radioactive formulation under sterile conditions directly prior to administration to a patient. In addition, it is desirable with a view to producing high quality commercial products that meet the rigorous standards of the cGMP principles that the manufacturing process is amenable to automation with minimal manual intervention during dose preparation.

The present invention relates to compositions, methods and procedures for removal of cationic daughter nuclides from a radiopharmaceutical preparation containing a parent radionuclide, which may be in solution or stably chelated to an entity comprising a ligand and a targeting moiety, i.e. the parent radionuclide is complexed or complexable to a ligand which is itself conjugated to a targeting moiety (such as an antibody). In particular, the present inventors have surprisingly established that daughter radionuclides may be safely and reliably captured onto various selective binders, either continuously during storage of the radioisotope

and/or shortly before administration of the radioisotope in the form of a radiopharmaceutical. The radionuclides captured by the selective binders are particularly alpha-emitting radionuclides or generators for alpha-emitting radionuclides typically formed during the decay of the parent alpha-emitting radionuclide and/or by further decay of the resulting daughter nuclides. A typical decay chain for ^{227}Th is described herein and the isotopes indicated in that chain form preferred daughter isotopes which may be removed and/or captured in the various aspects of the present invention. The final therapeutic formulations obtained from application of the invention are suitable for use in the treatment of both cancer and non-cancerous diseases.

Alternative phrased; the invention provides a composition allowing removal of radioactive daughter nuclides during storage and/or immediately before administration (e.g. injection) wherein ingrown radioactive decay products are removed. This leads to minimal co-administration of daughter nuclides and hence minimizing radiation dose and radiation damage to normal and non-target tissues.

Thereby, only the concentration and the half-life of the parent radionuclide and of daughter nuclides formed in vivo have to be taken into consideration when calculating the radioactive dose obtained by the patient. Most importantly this leads to a reproducible situation with regard to the relation between efficacy and adverse effects. Thus, the available therapeutic window will not change with storage time of the pharmaceutical preparation.

Phrased differently; by applying the invention the relation between desired anti-tumour effects and adverse effects may be directly related to the measured concentration of the primary nuclide and becomes independent of the time of storage of the pharmaceutical preparation. In situations where the concentration of the primary alpha-emitting radionuclide may be determined by measuring one or more parallel emissions of gamma radiation, sufficiently separate from and gamma emission from the daughter emissions, this may be performed using standard equipment at the radiopharmacy. In fact, if the drug product is pure with respect to the parent nuclide, the relevant dose of the pharmaceutical preparation will depend only on the time after manufacturing and may be tabulated. In principle there is no need for further measurements at the clinic and the corresponding

radiopharmaceutical could be handled in analogy to any other toxic pharmaceutical (although such a procedure would counter current practice, which is based on the fact that radioactivity *can* be easily measured). The enablement of this new and simplified procedure for clinical handling of targeted alpha-emitting radiotherapeutics is an important aspect of the invention.

In a further embodiment, the invention relates to the provision of a kit for pharmaceutical preparation. Kits are typically supplied to the hospital pharmacy or centralised radiopharmacy and may be prepared for administration shortly (e.g. less than 6 hours) or immediately (e.g. less than one hour) before administration. It would be a considerable advantage if purification of the desired alpha-emitting radionuclide could be accomplished at the time of readying of the pharmaceutical preparation for administration. It would be a further advantage if that purification could be carried out without undue burden and without complex handling, since all handling of radioactive materials is desirably minimised.

A kit according to the invention may be in the form of a device, e.g. a cassette laboratory, where tubes or vials containing the various reagents are attached, as well as a syringe to contain the final dosage form of the injectable pharmaceutical preparation. The device performs the operations that would else be performed manually.

It has been established by the present inventors that certain selective binding materials, particularly in the form of or immobilised on a solid or gel, will, to a high extent, retain cationic daughter nuclides after decay of the parent nuclide. The selectivity of these materials allows retention of the daughters but allows the complexed parent radioisotope (e.g a thorium isotope such as ^{227}Th, complexed by a ligand optionally attached to a biomolecule) to pass unhindered through the filter or to be left in solution while the daughters are retained. This provides a considerable advantage in the preparation and delivery of high quality radiopharmaceuticals which can be prepared directly or shortly prior to administration but delivered with a relatively low level of contamination from uncomplexed daughter radionuclides.

Summary of the Invention

In a first aspect, the invention therefore provides a pharmaceutical process capable of producing a complexed alpha-emitting radionuclide-(optionally in the

form of a biomolecule conjugate). Preferably said process comprises as key component a selective binder (such as a solid-phase resin filter) capable of selectively absorbing, binding, complexing or otherwise removing from solution uncomplexed daughter nuclides formed during decay of thorium-227. These may be the direct daughter nuclides or those further down the radioactive decay chain. In particular, ^{223}Ra and its well known decay products (including ^{219}Rn, ^{215}At, ^{215}Po, ^{211}Po, ^{211}Bi, ^{211}Pb, ^{207}Pb and ^{207}Tl) are typical daughter isotopes which will desirably be removed, as are any shown in the thorium decay chain indicated herein.

A key aspect of the present invention is thus a method for generating a purified solution of at least one complexed alpha-emitting radionuclide, said method comprising contacting a solution comprising said least one alpha-emitting radionuclide complex and at least one daughter nuclide with at least one selective binder for said at least one daughter nuclide and subsequently separating said solution of at least one alpha-emitting radionuclide complex from said at least one selective binder.

In all aspects of the present invention, the daughter nuclides are generally uncomplexed. This may be the result of the kinetic recoil generated upon alpha-decay and/or as a result of differing complexation properties between the parent nuclide and the daughter. All radionuclide used in the present invention are typically "heavy metal" radionuclides having, for example, an atomic mass greater than 150 amu (e.g. 210 to 230). Typical alpha-emitting heavy-metal radionuclides include ^{211}At, ^{212}Bi, ^{223}Ra, ^{224}Ra, ^{225}Ac and ^{227}Th. Preferred alpha-emitting (parent) radionuclides include alpha-emitting thorium radionuclides such as ^{227}Th, which is most preferred.

The inventors have surprisingly established that appropriate selective binding materials (as described herein, e.g. solid-phase resin materials) are highly effective in absorbing unwanted uncomplexed daughter ions in the preference to complexed thorium optionally conjugated to targeting moieties (such as biomolecules). Consequently, in a second aspect the present invention provides a method for generating an injectable solution comprising at least one complexed alpha-emitting radionuclide substantially free from daughter nuclides, said method comprising contacting a sample with a suitabel selective binder, Preferably this contat will be

by means of a simple purification/ filtration step yielding highly radiochemically pure pharmaceutical preparations comprising high levels of the desired alpha-emitting (e.g. thorium) complex (optionally conjugated to a targeting moiety). Typically the separation of the labelled thorium-complex (and optionally conjugate) will be followed immediately by a sterile filtration. This is particularly appropriate as the final step prior to administration.

The present invention thus provides a method for the removal of at least one daughter radionuclide from a solution comprising at least one alpha-emitting radionuclide complex, said method comprising contacting said solution with at least one selective binder for said at least one daughter nuclide.

In the present invention, the alpha-emitting radionuclide which is desired for administration (the "parent" radionuclide) will be as described herein and will be "complexed" or "in the form of a complex". These terms take their common meaning in that the alpha-emitting radionuclide will be in the form of a coordination complex comprising a cation of the heavy metal radionuclide and at least one ligand bound thereto. Suitable ligands, including those described herein, are well known in the art.

Since pharmaceutical preparations may be generated from the solutions of the present invention, the invention provides such pharmaceutical preparations. These will comprise a solution of the alpha-emitting radionuclide and will be substantially free of daughter nuclides as indicated herein. In a pharmaceutical preparation of the invention, the alpha-emitting radionuclide will be complexed by at least one ligand and the ligand will be conjugated to a targeting (specific binding) moiety as described herein. The solutions of the invention may be provided directly in an administration device (such as a syringe, cartridge or syringe barrel) ready for administration, with the invention allowing for purification of the solution into a pharmaceutical preparation at the time of administration and even by the act of administration (e.g. by administration through a suitable specific binder in the form of a syringe filter). Thus the devices of the invention may be administration devices such as syringes. The invention thus provides in another aspect, an administration device comprising a solution as described herein. Such a device may additionally

comprise, for example, a filter, such as a sterile filter. Syringe-filters are appropriate for syringes and similar devices.

The invention thus provides an administration device comprising a solution of at least one complexed alpha-emitting radionuclide and at least one daughter nuclide, said device further comprising a filter containing at least one selective binder for said daughter nuclide. Other devices of the invention which will also comprise a solution of alpha-emitting radionuclide, a ligand, a targeting moiety and a selective binder, will be in the form of (preferably disposable) cartridges, cassettes, rotors, vials, ampoules etc which may be used in the methods of the invention, by manual steps and/or by automated procedures in an automated apparatus.

A further key aspect of the present invention is a kit by which a pharmacuetical preparation may be generated. In a further aspect, the invention therefore provides a kit for the formation of a pharmaceutical preparation of at least one alpha-emitting radioisotope, said kit comprising:

i) a solution of said at least one alpha-emitting radioisotope and at least one daughter isotope;

ii) at least one ligand;

ii) a specific binding moiety;

iii) at least one selective binder for said at least one daughter isotope.

Wherein said alpha-emitting radioisotope is complexed or complexable by said ligand which is conjugated or conjugatable to said specific binding moiety.

In one embodiment, the alpha-emitting radionuclide will be complexed by the ligand but may not be conjugated to the specific binding (targeting) moiety. Alternatively, the ligand may be stably conjugated to the targeting moiety and present in a separate vessel from the radio-isotope. Having the organic molecules of the complex (the ligand and/or the targeting moiety) separate from the alpha-emitter reduces the radiation damage (e.g. oxidation) of the organic material due to exposure to alpha-irradiation during storage.

In one embodiment, the kit may be provided as two vials. Such a kit comprises a radioisotope (e.g. thorium-227) vial and a second vial containing a

buffered solution of biomolecule-conjugate suitably conjugated with a ligand (chelate) which complexes thorium-227. Immediately prior to drug product preparation the thorium-227 vial is mixed with the biomolecule-conjugate solution.

The capture of free (uncomplexed) radionuclides, particularly free daughter radionuclides, from a solution containing at least one complexed alpha-emitting radioisotope (such as a parent radioisotope) and at least one organic component (such as a complexing agent and/or targeting agent) serves to reduce the exposure of the organic component to ionising radiation from the further decay of the free radionuclides (e.g. daughters). Correspondingly, in a further aspect the invention also provides a method for reducing the radiolysis of at least one organic component in a solution comprising at least one alpha-emitting radionuclide complex, at least one daughter radionuclide and at least one organic component (such as a complexing agent and/or targeting agent), said method comprising contacting said solution with at least one selective binder for said at least one daughter nuclide. This method may be illustrated by a reduction in H_2O_2 concentration in the solution.

In all appropriate aspects of the present invention, the "daughter" radionuclide (equivalently radioisotope) will typically be "free" in solution. This indicates that the radionuclide is in the form of a dissolved ion and is not (or not to any significant degree) complexed or bound by ligands in the solution. The daughter radionuclide may obviously be bound to the specific binder but generally this will not be in solution (as described herein). As used herein, the term "daughter" radionuclide takes its common meaning in the art, in that such nuclides are generated directly or indirectly from the decay of another radioisotope. In the present case, at least one "daughter" radionuclide present in the solutions referred to herein in any and all aspects of the invention will be a direct (first generation) or indirect (second, third or subsequent generation) decay product of the radionuclide present in the alpha-emitting radionuclide complex. It is preferably that at least the first generation decay product of the radionuclide comprised in the alpha-emitting radionuclide complex will be present in such solutions and will be bound by the selective binder.

Detailed Description

As described previously it is dependent on time of storage and transportation how much ingrowth of daughter radionuclides are present in thorium vial at the time of complexation. The daughter nuclides however do not effect the complexation of alpha-emitting radionuclide (thorium-227) to the biomolecule conjugate as the chelate is chosen such that the desired radionuclide (e.g. thorium) has a significantly higher affinity for the chelate compared to the daughters. In a second, batch-wise process, the daughter nuclides are separated from the now thorium-labelled biomolecule by filtration through a specific binder. This may be in the form of a solid-phase filter cartridge.

This process of separation of the alpha-emitting material from the organic ligand and/or targeting moiety has the added advantage of reducing the rate of radiolysis (e.g. of the biomolecule carrier and/or chelating moiety) of the radiopharmaceutical and may be applied to all aspects of the invention. Because the radioactive product is manufactured 'closer to bedside' than other strategies currently being employed, the material should have higher radiochemical purity and/or higher purity of the organic material (ligand and/or targeting moiety components). This is beneficial in terms of maintaining shelf-life requirements.

The injectable solutions formed or formable by the methods and uses of the invention are highly suitable for use in therapy, particularly for use in the treatment of hyperplastic or neoplastic disease. Pharmaceutical preparations formed or formable by the various methods of the invention form further aspects of the present invention.

As used herein, the term "pharmaceutical preparation" indicates a preparation of radionuclide with pharmaceutically acceptable carriers, excipients and/or diluents. However, a pharmaceutical preparation may not be in the form which will ultimately be administered. For example, a pharmaceutical preparation may require the addition of at least one further component prior to administration and/or may require final preparation steps such as sterile filtration. A further component can for example be a buffer solution used to render the final solution suitable for injection in vivo. In the context of the present invention, a pharmaceutical preparation may contain significant levels of uncomplexed

radionuclides resulting from the radioactive decay chain of the desired radionuclide complex which will preferably be removed to a significant degree by a method according to the present invention before administration. Such a method may involve the batch-wise removal (eg. selective binding, chelation, complexation or absorption) of such uncomplexed daughter radionuclides over a significant part of the storage period of the preparation, or may take place at the final stage, immediately before administration.

In contrast to a pharmaceutical preparation, an "injectable solution" or "final formulation" as used herein indicates a medicament which is ready for administration. Such a formulation will also comprise a preparation of complexed radionuclide with pharmaceutically acceptable carriers, excipients and/or diluents but will additionally be sterile, of suitable tonicity and will not contain an unacceptable level of uncomplexed radioactive decay products. Such levels are discussed in greater detail herein. Evidently, an injectable solution will not comprise any biopolymer component, although such a biopolymer will preferably have been used in the preparation for that solution as discussed herein.

Injectable solutions formed or formable by any of the methods of the present invention form a further aspect of the invention.

The invention provides a simple method or process for purification and preparation of a sterile final formulation of a radioactive preparation ready for administration, using specific binders in the form of absorbent materials and/or filters to capture unwanted radioactive decay products yielding rapid separation unwanted nuclides during storage and/or immediately prior to administration to a patient. The separation may be followed by the sterile filtration performed as the final formulation is drawn into the syringe, subsequently to be used for administration to the patient or may even take place as part of the act of administration.

Implemented as described, the invention provides a simple kit (as described herein) for purification and final formulation of a radioactive medicament for use in therapy. The kits of the invention may for example include a thorium vessel (such as a vial, syringe or syringe barrel) containing a solution of a radioactive thorium salt (e.g. a ^{227}Th salt), a vessel (e.g. vial) with a pharmaceutical solution (e.g. a ligand

conjugated to a targeting moiety such as an antibody or recepor), a filter containing at least one specific binder for the daughter nuclide(s), optionally a sterile filter and a syringe. The components of the kit may be separate or coupled together into one unit or flow cell forming a closed system therefore reducing the likelihood of introducing unwanted byproducts during the manufacture. Avoiding steps during which radiochemical contamination can be caused is an obvious advantage of kits having components fully or partially sealed together such that material remains within the kit for as many process steps as possible.

The invention provides for the use of the procedure for preparation of a final formulation for injection, for example using components provided as a kit. The procedure of any of the methods and/or uses of the invention may include an incubation step where the solution or pharmaceutical preparation is mixed for example by gentle shaking, to enable optimal complexation of thorium with the biomolecule-chelate conjugate, followed by filtration to remove unwanted daughter nuclides.

One example procedure for the formation of an injectable solution of an alpha-radionuclide comprises the steps of:

a) Combining a first solution comprising a dissolved salt of an alpha-emitting radionuclide and at least one daughter nuclide with a second solution comprising at least one ligand conjugated to at least one targeting moiety;

b) Incubating the combined solutions at a suitable temperature (e.g. 0°C to 50°C, preferably 20°C to 40°C) for a period to allow complex formation between said ligand and said radioisotope whereby to form a solution of at least one complexed alpha-emitting radioisotope;

c) Contacting said solution of at least one complexed alpha-emitting radioisotope with at least one selective binder for at least one of said dauther nuclides.

d) separating said solution of at least one complexed alpha-emitting radionuclide from said at least one selective binder.

In the method of formation of an injectable solution, steps c) and d) constitute a purification method which may be in accordance with any of the appropriate

embodiments of the invention as described herein. In this embodiment, the nuclides, binders, ligands and all appropriate aspects will be as indicated herein.

The pharmaceutical preparations of the invention, along with the purified solutions generated by the methods of the invention and the injectable solutions formed by the methods of the invention will desirably have a low concentration of uncomplexed daughter metal ions. Typically, for example, the solution concentration of daughter nuclides should preferably contribute no more than 10% of the total count of radioactive decays per unit time (from the solution), with the remainder being generated by decay of the complexed (e.g. thorium) alpha radionuclide. This will preferably be no more than 5% of the total count and more preferably no more than 3%.

Preferably the alpha radionuclide conjugates of this invention contain thorium-227 wherein the process is most effective in removing preferably ^{223}Ra..Other daughter isotopes as indicated herein may also be removed. In the pharmaceutical preparations of the invention and correspondingly in the resulting solutions for injection, as well as in all aspects of the invention, the radionuclide is complexed or complexable by means of a suitable complexing/chelating entity (generally referred to herein as a ligand). Many suitable ligands are known for the various suitable alpha-emitting radionuclides, such as those based on on DOTA (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid) and other macrocyclic chelators, for example containing the chelating group hydroxy phthalic acid or hydroxy isophthalic acid, as well as different variants of DTPA (diethylene triamine pentaacetic acid), or octadentate hydroxypyridinone-containing chelators. Preferred examples are chelators comprising a hydroxypyridinone moiety, such as a 1,2 hydroxypyridinone moiety and/or a 3,2- hydroxypyridinone moiety. These are very well suited for use in combination with ^{227}Th. In one embodiment of the invention, the alpha-emitting radionuclide complex is an octadentate 3,2-HOPO complex of a ^{227}Th ion.

In the pharmaceutical preparations of the invention and correspondingly in the resulting solutions for injection and all other aspects of the invention, the at least one complexed alpha-emitting radionuclide is preferably conjugated or conjugateable to at least one targeting moiety (also described herein as a specific

binding moiety). Many such moieties are well known in the art and any suitable targeting moiety may be used, individually or in combination. Suitable targeting moieties include poly- and oligo-peptides, proteins, DNA and RNA fragments, aptamers etc. Preferable moieties include peptide and protein binders, e.g. avidin, strepatavidin, a polyclonal or monoclonal antibody (including IgG and IgM type antibodies), or a mixture of proteins or fragments or constructs of protein. Antibodies, antibody constructs, fragments of antibodies (e.g. Fab fragments, single domain antibodies, single-chain variable domain fragment (scFv) etc), constructs containing antibody fragments or a mixture thereof are particularly preferred.

Antibodies, antibody constructs, fragments of antibodies (e.g. Fab fragments or any fragment comprising at least one antigen binding region(s)), constructs of fragments (e.g. single chain antibodies) or a mixture thereof are particularly preferred. Suitable fragments particularly include Fab, F(ab')2, Fab' and/or scFv. Antibody constructs may be of any antibody or fragment indicated herein.

In addition to the various components indicated herein, the pharmaceutical preparations may contain any suitable pharmaceutically compatible components. In the case of radiopharmaceuticals, these will typically include at least one stabiliser. Radical scavengers such as ascorbate, p-ABA and/or citrate are highly suitable. Serum albumin, such as BSA, is also a suitable additive, particularly for protection of protein and/or peptide components such as antibodies and/or their fragments.

In the methods and uses of the present invention, the contacting between the solution part of the pharmaceutical preparation and the selective binding agent (e.g. solid-phase resin filter) may take place over an extended period of time (e.g. at least 30 minutes, such as at least one 1 hour or at least 1 day). In this embodiment, the selective binder may be present with the solution of alpha-emitting radionuclide during storage. In an alternative embodiment, however, said contacting will occur rapidly (such as over less than 30 minutes, less than 10 minutes, or less than 5 minutes (e.g. less than 1 minute or no more than 30 seconds). In such an embodiment, the selective binder will typically be in the form of or bound to a solid material (as described herein) and may be formed into a separation column, pad or filter through which the solution may be passed. Such passage may be under gravity or by centrifugal force, may be driven by suction or most preferably will be driven

by positive pressure, such as by application of pressure to a syringe barrel. In such a case, the contacting takes place.as the solution is pushed through the filter/pad/column. Although rapid separation is the most preferred method, alternatively, the contacting and filtration step may be carried out over longer time periods (e.g. 3 to 20 minutes) to ensure maximum radiochemical purity.

In an alternative embodiment, said contacting/ filtering takes place for no more than 30 seconds preferably no more than 1 minute followed by a sterile filtration and will thus also generate a sterile solution suitable for injection. Correspondingly, the kits of the invention may optionally and preferably additionally comprise a filter (e.g. of pore size 0.45 μm or of pore size of about 0.22 μm). In all cases filtration through a filter of pore size no larger than 0.45 μm, preferably no larger than 0.22 μm is preferred. Such a filter may serve to retain the selective binder employed in the various aspect of the invention.

In the various aspects of the present invention, the ligand moiety is generally conjugated or conjugatable to at least on specific binding (targeting) moiety. Such conjugation may be by means of a covalent bond (such as a carbon-carbon, amide, ester, ether or amine bond) or may be by means of strong non-covalent interactions, such as the binding of a pair of specific-binding moieties, such as biotin to avidin / streptavidin. Most preferably the ligand is conjugated to the targeting moiety by means of a covalent bond, optionally by means of a linker (such as a C1 to C10 alkyl group independently substituted at each end by an alcohol, acid, amine, amide, ester or ether group)

In all aspects of the present invention, the selective binder is typically a solid or gel, or is immobilised on a solid or gel matrix (such as a porous matrix or membrane). This allows for ease of handling and separation and also for ease of contacting the selective binder with the alpha-emitting radioisotope complex and subsequent separation. A "solid" material may be taken as one which will hold its shape under gentle mechanical pressure including that provided by manual use of a syringe or by the pressure provided in an automated apparatus. Typically the selective binder will be in the form of or immobilised to a porous material such that the solution can pass though the pores of the material. Suitable matrices for supporting selective binders are discussed herein and will be well known to those of

skill in the art. These include metal oxides (e.g. silica, alumina, titania) glass, metal, plastics etc. selective binders may be immobilised on the surface of such matrices or may form porous matrices in themselves. Any of the materials indicated may form a support in the form of membranes, resin beads, gel beads, self-assembled lipid structures (e.g. liposomes), microparticles, nanoparticles, powders, crystals and polymer structures as appropriate. Evidently more than one such structure may be used.

As the selective binding material will be chosen at least one substance having greater affinity for the daughter radionuclide(s) in solution over the alpha-emitting radionuclide complex. Such materials suitable for selective binders include at least one of cation exchange resins, size exclusion resins, zeolites, molecular sieves, alginates, liposomes, phosphonates, polyphosphonates, phospholipids, glycolipids, lipo-proteins, oligosaccharides, ferritin, transferrin, phytic acid and co-precipitation agents. Highly preferred selective binders include cation exchange resins, hydroxyapatite, and zeolites.

In one embodiment, the selective binders of the present invention do not comprise any polysaccharide. In one embodiment the selective binders do not comprise any alginate. In a further embodiment, the binder comprises, consists essentially of or consists of at least one inorganic material, such as at least one ceramic material. Inorganic resins (e.g. inorganic ion exchange resins), metal oxides (such as silica, alumina, titania, especially when porous such as mesoporous), hydroxyapatite (including substituted hydroxyapatites), molecular sieves and zeolites form highly preferred inorganic binding materials.

Details of certain materials suitable for use as selective binding agents are indicated below in Table 1. Examples given in the description column form preferred choices of material for use as selective binders in the present invention.

Table 1:

Material	Description
Cation exchange resins	An insoluble matrix normally in the form of small beads, usually white or yellowish, fabricated from an organic polymer substrate. The material has highly developed structure of pores on the surface of which are sites with easily trapped and released ions. The trapping of ions takes place only with simultaneous releasing of other ions; thus the process is called ion-exchange.
Size exclusion/gel filtration resins	Size-exclusion chromatography (SEC) is a chromatographic method in which molecules in solution are separated by their size, and in some cases molecular weight.
Molecular sieves	material containing tiny pores of a precise and uniform size that is used as an adsorbent
Alginate	(= salts of alginic acid) linear copolymer with homopolymeric blocks of (1-4)-linked β-D-mannuronate (M) and its C-5 epimer α-L-guluronate (G) residues, respectively, covalently linked together in different sequences or blocks
Liposomes (sterically stabilized)	artificially-prepared vesicle primarily composed of a lipid bilayer. Liposomes are composed of natural phospholipids, and may also contain mixed lipid chains with surfactant properties. A liposome design may employ surface ligands.
(Poly-) phosphonate	Phosphonates or phosphonic acids are organic compounds containing C-PO(OH)2 or C-PO(OR)2 groups (where R=alkyl, aryl). Phosphonic acids are known as effective chelating agents. The introduction of an amine group into the molecule to obtain -NH2-C-PO(OH)2 increases the metal binding abilities of the phosphonate.
Nano-particles	nanoparticles are sized between 100 and 1 nano-meters. Large surface to volume ratio. Liposomes are an example of nanoparticles.
Phospho-lipids	A class of lipids that are a major component of all cell membranes as they can form lipid bilayers. Most phospholipids contain a diglyceride, a phosphate group, and a simple organic molecule as choline.
Glycolipids	lipids with a carbohydrate attached

Material	Description
Co-precipitation	The carrying down by a precipitate of substances normally soluble under the conditions employed. Since the trace element is too dilute (sometimes less than a part per trillion) to precipitate by conventional means, it is typically coprecipitated with a *carrier*, a substance that has a similar crystalline structure that can incorporate the desired element. Occurs by inclusion, adsorption or occlusion.
Ferritin/ Apoferritin, transferrin / apotransferrin	Ferritin is a globular protein complex keeping iron in a soluble and non-toxic form. Ferritin that is not combined with iron is called apoferritin. Transferrins are iron-binding blood plasma glycoproteins that control the level of free iron in biological fluids.
Lipo-proteins	a biochemical assembly that contains both proteins and lipids
Cyclo-dextrines	cyclic oligosaccharides
Phytic acid (phytate when in salt form)	Phosphorus compound with chelating actions. It occurs naturally in plants as the insoluble calcium magnesium salt and is a major source of phosphate in the diet, although there is debate about its bioavailability. Excess intake of phytate has been associated with deficiencies of elements such as calcium, iron, and zinc.
Surface modifications	Agents with possible affinity for 223-Ra: Phytic acid Phospholipids Phosphonates Carriers: Liposomes Mikroparticles/ nanoparticles/ resins/ alginate/ polymer beads/ cyclodextrines

In one aspect, the selective binder(s) are in the form of a column or filter. In this and other appropriate embodiments, the means of contacting will be the flow of solution through or past the selective binder. Alternatively, where the selective binder is immobilised on a support then the flow may be through or past such a support. Subsequent flow through a sterile-filtration membrane (as described herein) is preferred.

The injectable solution obtained from compositions or pharmaceutical formulations of the invention are suitable for treatment of a range of diseases and are particularly suitable for treatment of diseases relating to undesirable cell proliferation, such as hyperplastic and neoplastic diseases. For example, metastatic and non-metastatic cancerous diseases such as small cell and non-small cell lung cancer, malignant melanoma, ovarian cancer, breast cancer, bone cancer, colorectal cancer, pancreatic cancer, bladder cancer, cervical cancer, sarcomas, lymphomas, leukemias, tumours of the prostate, and liver tumours are all suitable targets. The "subject" of the treatment may be human or animal, particularly mammals, more particularly primate, canine, feline or rodent mammals.

Other aspects of the invention are the provision of a composition according to the invention, or alternatively the use of a composition according to the invention in the manufacture of a medicament for use in therapy. Such therapy is particularly for the treatment of diseases including those specified herein above. By "treatment" as used herein, is included reactive and prophylactic treatment, causal and symptomatic treatment and palliation.

Use of the medicament resulting from the invention in therapy may be as part of combination therapy, which comprises administration to a subject in need of such treatment an injectable solution according to the invention and one or more additional treatments. Suitable additional treatments include surgery, chemotherapy and radiotherapy (especially external beam radiotherapy).

In a further aspect the invention encompasses apparatus, kit as described herein. Such kits will comprise an alpha-emitting radioisotope, a ligand, a targeting moiety and a selective binding material for binding daughter nuclides. Typically, in use, the alpha-emitting radionuclide will either be present as an alpha-emitting radionuclide complex, or will be formed into such complex by contact between a first solution of said kit (comprising the alpha-emitting radionuclide and any daughter nuclides) and a second solution of said kit (comprising the ligand conjugated to the targeting moiety). Following conjugation the alpha-emitting radionuclide complex will be contacted with the selective binder. That contact may be in any way described herein, but will preferably be by passing the alpha-emitting

radionuclide complex solution through a column, pad, filter, membrane or plug of selective binding material.

The kits of the present invention will generally include the selective binding material in the form of a filter or column. The alpha-emitting radionuclide solution will be present in a first vessel but this and all vessels referred to herein may be a vial, syringe, syringe barrel, cartridge, cassette, well, ampoule or any other appropriate vessel as well as a part of such a vessel, such as one well in a plate or one void within a multi-reagent cartridge or cassette. The first and second vessels, where present, may form part of the same device (e.g. may be separate wells or voids in a multi-component plate or cassette) and may be in fluid communication with each other, optionally by means of removing a seal, plug or opening a tap or removing a restriction, clamp etc to allow mixing of solutions. Such mixing may be initiated manually or may be the result of a manipulation within an automated apparatus.

One embodiment of the kits of the invention are in the form of cartridges for an automated apparatus, for example, an automated synthesiser. Such automated apparatus allow for performing the methods of the invention with minimal manual intervention to ensure compliance with cGMP principles. Thus, a typical apparatus includes an automated synthesiser such as the GEHC FastLab or TracerLab which will contain or be loaded with the kit or device of the present invention. An automated apparatus comprising a kit or device of the invention thus forms a further aspect of the invention. The kit of the invention may be in the form of a device, cartridge, rotor, reagent pack etc for any of these or any similar apparatus. An automated apparatus may be used for fully automated process comprising radionuclide (e.g. thorium-227) complexation to a ligand/biomolecule conjugate, removal of daughter nuclides by filtration on a selective binder (e.g. solid-phase resin) sterile filtration and dispensing into a drug product vial. Thus, the various methods of the invention may be carried out by means of an automated apparatus such as one containing a kit or device as described herein.

In a related embodiment, the invention provides for an administration device. Such a device may contain a solution of alpha-emitting radionuclide complex and daughter nuclides and will comprise a selective binder for said daughter nuclide(s).

In use, such an administration device may concomitantly remove daughter nuclides by passage of the solution through or past the selective binder and also deliver the resulting purified solution to a subject.

The injectable solutions formed and formable from the pharmaceutical compositions of the invention and those formed by use of the kits of the invention will evidently form a further aspect of the invention. Such solutions may be, for example an injectable solution comprising a solution of at least one complexed alpha-emitting radionuclide and at least one pharmaceutically acceptable carrier or diluent wherein the solution concentration of any uncomplexed ions resulting from the radioactive decay chain of said least one complexed alpha-emitting radionuclide is no greater than 10% of the solution concentration of said least one complexed alpha-emitting radionuclide.

One aspect of the present invention relates to a method for reducing the radiolysis of at least one organic component in a solution. Generally this will be a solution as described herein in respect of any embodiment and may comprise at least one alpha-emitting radionuclide complex, at least one daughter radionuclide and at least one organic component. Typically in this and all embodiments, the daughter will be a daughter isotope formed by radioactive decay of at least one alpha-emitting radionuclide in or from a corresponding complex. The organic material may be any organic component including any pharmaceutically acceptable carrier, diluent, buffer etc (any of which, organic or not, may be incorporated into the solutions described in relation to the present invention). Most commonly the organic component will comprises a complexing agent and/or targeting agent, which will typically be the complexing agent of the said complex as described herein. The targeting agent may be any suitable targeting moiety (such as an antibody, antibody fragment (Fab, $F(ab')_2$ scFv etc), antibody or fragment conjugates etc). The targeting agent will typically be conjugated to the complex by covalent or non-covalent conjugation. By contacting such a solution at least one selective binder for the at least one daughter nuclide (especially at least one selective binder as described in any embodiment herein but most particularly inorganic binders such as hydroxyapatite) then the daughter radionuclides may be sequestered out of solution and separated from both the organic material and other materials, including water,

that can readily be ionised or converted into a radical form. As well as direct benefit from reduced direct radiolysis, this reduction in radiolysis will evidently also be an indirect benefit in that the lower concentration of radical and oxidising species will reduce undesirable reactions with the organic material of the complex or targeting moiety. As an embodiment of this method, the invention also provides a method for reducing the H_2O_2 concentration in a solution comprising at least one alpha-emitting radionuclide complex, at least one daughter radionuclide and optionally at least one organic component (such as a complexing agent and/or targeting agent), said method comprising contacting said solution with at least one selective binder for said at least one daughter nuclide.

In all aspects, "reducing" radiolysis or the concentration of a component relates to a reduction in comparison with a control solution containing all corresponding component of the solution except for the specific binder(s). Similarly, "removing" relates to removing a radionuclide from free solution, such as by entrapping that radionuclide within a separable material such as a gel or solid (such as a ceramic, porous solid etc).

The invention will now be illustrated by reference to the following non-limiting Examples, and the Figures below, in which:

Figure 1 shows the generation of hydrogen peroxide by radiolysis of water in the presence or absence of a selective binder

EXAMPLE 1

Radium-223 uptake on gravity columns using ceramic hydroxyapatite

100 mg ceramic hydroxyapatite was weighed out and transferred to the columns. HEPES buffer (5 mM, pH 8) was used to equilibrate the column (3 x 1 ml). 1 ml HEPES buffer was then added to the column which was left standing over night before 140 kBq radium-223 in 1 mL was loaded. Uptake was immediate. The column was then washed with HEPES buffer (3 x 1 ml), before uptake of radium-223 on the column material was determined using a HPGe-detector instrument (Ortec, Oak Ridge, TN).

The material removed 98.9 % of radium-223 and daughter nuclides (Table 2).

Table 2 Average percentage retention of radium-223 for ceramic hydroxyapatite (n=3).

Samples	Average retention of radium-223 (%)
Ceramic hydroxyapatite	98.9

EXAMPLE 2

Purification of a Targeted Thorium Conjugate in phosphate buffer on spin columns with propylsulfonic acid silicabased cation exchange resin

A trastuzumab chelator conjugate prepared as described previously (WO2011/098611A) was labeled with thorium-227 (forming a Targeted Thorium Conjugate, TTC), using thorium-227 stored for 5 days in HCl following purification and hence containing ingrown radium-223 and progenies of radium-223 decay. Each sample contained 0.21 mg TTC, 520 kBq thorium-227 and 160 kBq radium-223 in 300 µl saline phosphate buffer pH 7.4 (Biochrome PBS Dulbecco, Cat no L1825). The sample was added to a column with 15 mg propylsulfonic acid silica based cation exchange resin. The columns were centrifuged (10 000 rcf, 1 min) and the eluate collected. The distribution of thorium-227 (TTC) and radium-223 between the column and eluate was determined using a HPGe-detector instrument (Ortec, Oak Ridge, TN).

The retention of TTC (represented by thorium-227) and radium-223 on the column was 5.5 and 99.1 %, respectively (Table 3).

Table 3 Retention of Targeted Thorium Conjugate (TTC) and radium-223 after purification on spin columns with cation exchange resin

Amount of cation exchange resin (mg)	TTC on column (%)	radium-223 on column (%)
15	5.5	99.1

EXAMPLE 3

Removal of radium-223 in citrate and phosphate buffer on spin columns with propylsulfonic acid silicabased cation exchange resin

160 kBq radium-223 in 300 µl 50 mM citrate buffer pH 5.5 with 0.9 % sodium chloride or saline phosphate buffer pH 7.4 (Biochrome PBS Dulbecco, Cat no L1825) was added to a column with 60 mg propylsulfonic acid silica based cation exchange resin. The columns were then centrifuged (10 000 rcf, 1 min) and the eluate collected. The distribution of radium-223 between the column and eluate was determined using a HPGe-detector instrument (Ortec, Oak Ridge, TN).

The retention of radium-223 on the column was 96.5 % for the citrate buffer and 99.6 % for the phosphate buffer, respectively (Table 3).

Table 3 Retention of radium-223 after purification on spin columns with cation exchange resin

Buffer type	**Average radium-223 on column (%)**
Citrate	96.5
phosphate	99.6

Example 4 - Further comparison of selective binder materials

Strontium and calcium alginate gel beads, DSPG liposomes, ceramic hydroxyapatite, Zeolite UOP type 4A, and two cation exchange resins (AG50WX8 and SOURCE 30 S) were selected as materials to be studied for radium-223 uptake . Passive diffusional uptake of nuclides was tested by having materials present as suspensions in the formulation. Measurements were taken with the aid of a Germanium detector after 1 hour equilibration at 25 °C with shaking. Removal of free nuclides on gravity columns was also studied.

Uptake of radium-223

All materials, to some degree, removed radium-223 and daughters by passive diffusional uptake ranging from 30.8 ± 5.8 to 95.4 ± 2.5 % uptake at the selected experimental conditions. All the materials tested removed radium-223 and daughters on the gravity column set-up with near complete uptake. The results were significantly higher (~ 100 %) and with minimal variation (< 1 %) compared to passive diffusional uptake of radium-223, for all tested materials except for alginate gel beads (see Table 4).

Samples	Average uptake of radium-223 by passive diffusion (%)	Relative standard deviation uptake of radium-223 by passive diffusion(%)	Average uptake of radium-223 on gravity column (%)	Relative Standard deviation uptake of radium-223 on gravity column (%)
Liposomes	95.4	2.5	-	-
SOURCE 30S cation exchange resins	78.7	15.8	99.5	0.1
Ceramic hydroxyapatite	77.8	20.1	98.9	0.7
Calcium alginate gel beads	71.9	9.7	8.2	20.7
Strontium alginate gel beads	68.2	16.7	-	-
Zeolite UOP type 4A	49.7	7.4	-	-
Calcium alginate gel beads	33.1	1.7	-	-
AG50WX8 cation exchange resins	30.8	5.8	99.8	0.2

Various materials suitable for capturing radium-223 daughter isotopes have been identified. Strontium and calcium alginate gel beads, DSPG liposomes, ceramic hydroxyapatite, Zeolite UOP type 4A, and two cation exchange resins (AG50WX8 and SOURCE 30 S) were tested and all materials were found to remove radium-223 and daughters.

DSPG liposomes were superior when testing passive diffusional uptake while the other materials were suboptimal when used as suspensions and for uptake by passive diffusion. The cation exchange resins and ceramic hydroxyapatite were however excellent when used on gravity columns.

Example 5 – Reduction in radiolysis

Abstract

Formation of hydrogen peroxide (H_2O_2) in the water phase of the formulation was studied as a measure of radiolysis in the presence and absence of ceramic hydroxyapatite, which was one of the materials shown to efficiently bind the radionuclides from solution. Radiolysis and formation of free radicals in the water phase may degrade the radionuclide complex thus minimization of the generation and amount of H_2O_2 present is desirable. After 3 days the concentration of H_2O_2 in samples with ceramic hydroxyapatite was significantly lower than the controls, and the uptake of ^{223}Ra and ^{227}Th from solution was near complete.

Method

The UVmini-1240 single beam spectrophotometer (190 – 1100 nm) from Shimadzo (Kyoto, Japan) was used and light transmittance recorded at 730 nm for analyzes of the H_2O_2 concentration. Photometric mode was used where the absorbance of a sample is measured at a fixed wavelength (n=3). The cuvettes used were Plastibrand disposable 1.5 ml semi-micro (12.5 x 12.5 x 45 mm) cuvettes made of polystyrene.

A 0.5 mg/ml horseradish peroxidase solution and 2 mg/ml peroxidase substrate (2.2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt) solution were made by dissolution in metal free water. The peroxidase enzyme converts the peroxidase substrate from colorless to a green color with H_2O_2 as substrate. H_2O_2 standards at 1.765, 0.882, 0.441, 0.221, and 0.110 mmol/L H_2O_2 were made by diluting 30 % (w/w) H_2O_2 in metal free water (n=3). The linearity of the standard curve was R^2=0.9995.

Samples consisted of 100 mg/ml ceramic hydroxyapatite in 250 µl 9 mg/ml sodium chloride which was loaded with a freshly prepared ^{227}Th solution to a concentration of 0.5 kBq/µl (n=3).

Two types of control samples were analyzed; one negative control with only ^{227}Th and no binding material, and one positive control with binding material but no radioactive source (n=3). The negative controls were analyzed to check the homogeneity of the radionuclides in the sodium chloride solution and the amount of

H_2O_2 generated in the absence of binding material, while the positive controls were analyzed to see if a significant level of H_2O_2 was developed without the presence of radioactivity.

For calculation of the percentage uptake of radionuclides in ceramic hydroxyapatite samples and homogeneity of radionuclides in the negative controls, each sample or control was measured on the HPGe-detector before 60 µl supernatant was removed. Samples, controls and standards were further prepared for H_2O_2 analysis by mixing 900 µl 9 mg/ml sodium chloride with 50 µl peroxidase substrate solution, 25 µl horseradish peroxidase solution and 25 µl of the respective supernatant from sample, control or standard. The samples, control or standard were carefully mixed and measured immediately by UV-vis spectrophotometry. For radioactive samples and controls, the remaining sample volume was finally measured on the HPGe-detector. Uptake of radionuclides in ceramic hydroxyapatite or homogeneity of radioactivity in the sodium chloride solution was calculated by the aid of HPGe-spectra.

H_2O_2 concentration in the samples, standards and controls were analyzed by UV-vis spectrophotometry at 730 nm, at time points 0, 3, 7, 10 and 14 days.

Results

The measured level of H_2O_2 formed during 14 days storage in samples of suspended ceramic hydroxyapatite and freshly prepared ^{227}Th was significantly lowered compared to negative controls without ceramic hydroxyapatite (Fig. 1). The positive controls containing ceramic hydroxyapatite without radioactivity did not show any H_2O_2 formation outside the statistical error of the method (Fig. 1). The passive diffusional uptake of freshly prepared ^{227}Th in a suspension of ceramic hydroxyapatite was 81 ± 3 % at 90 minutes reaction time. The consecutive uptake of ^{227}Th and generated ^{223}Ra by ceramic hydroxyapatite was 99 ± 5 % and 102±12 %, respectively, when measured after 14 days incubation.

The measured reduction in H_2O_2 demonstrates a reduced production of radicals and oxidising agents due to radiolysis of the containing solution.

Claims:

1) A method for generating a purified solution of at least one alpha-emitting radionuclide, said method comprising contacting a solution comprising said least one alpha-emitting radionuclide complex and at least one daughter nuclide with at least one selective binder for said at least one daughter nuclide and subsequently separating said solution of at least one alpha-emitting radionuclide complex from said at least one selective binder.

2) A method for reducing the radiolysis of at least one organic component in a solution comprising at least one alpha-emitting radionuclide complex, at least one daughter radionuclide and at least one organic component, said method comprising contacting said solution with at least one selective binder for said at least one daughter nuclide.

3) A method for the removal of at least one daughter radionuclide from a solution comprising at least one alpha-emitting radionuclide complex, said method comprising contacting said solution with at least one selective binder for said at least one daughter nuclide.

4) A method as claimed in claim 2 or claim 3 wherein said solution is a pharmaceutical preparation.

5) A method as claimed in any of claims 2 to 4 further comprising separating said solution from said selective binder.

6) A method as claimed in any preceding claim wherein said alpha-emitting radionuclide is in the form of a complex with a ligand, wherein said ligand is conjugated to a specific binding moiety (such as an antibody).

7) A method as claimed in any preceding claim wherein said selective binder is in the form of, or is attached to, a solid support or gel support.

8) A method as claimed in claim 7 wherein said solid or gel support is in the form of, or attached to, least one selected from membranes, resin beads, gel beads, self-assembled lipid structures (e.g. liposomes), microparticles, nanoparticles, powders, crystals, ceramics and polymer structures.

9) A method as claimed in any preceding claim wherein said selective binder comprises at least one selected from cation exchange resins, size exclusion resins, zeolites, molecular sieves, hydroxyapatite, alginates, liposomes, phosphonates, polyphosphonates, phospholipids, glycolipids, lipo-proteins, oligosaccharides, ferritin, transferrin, phytic acid and co-precipitation agents.

10) A method as claimed in any preceding claim wherein said solution is contacted with said selective binder by means of flow of said solution through or past said selective binder or through or past a support upon which said selective binder is immobilised.

11) A method as claimed in claim 10 wherein said contacting is by means of a filtration in which said solution flows through or past said selective binder or through or past a support upon which said selective binder is immobilised.

12) A method as claimed in claim 11 wherein said filtration further comprises flowing said solution through a sterile filtration membrane.

13) A method as claimed in any preceding claim wherein said contacting takes place for a period of less than 30 minutes, such as less than 10 minutes, e.g. less than 5 minutes or less than 1 minute (e.g. no more than 30 seconds).

14) A method as claimed in any of claims 1 to 9 wherein said solution is contacted with said selective binder by means of addition of said selective binder and said solution to a vessel (e.g. a sealed or partially sealed vessel).

15) A method as claimed in claim 14 wherein said contacting takes place for 30 minutes or longer, (e.g. 1 hour or longer, such as 1 day or longer).

16) A method as claimed in any preceding claim wherein said alpha-emitting radioisotope is comprises at least one alpha-emitting thorium isotope, such as ^{227}Th.

17) A method as claimed in any preceding claim wherein said at least one daughter nuclide comprises at least one radium isotope, such as ^{223}Ra.

18) A kit for the formation of a pharmaceutical preparation of at least one alpha-emitting radioisotope complex, said kit comprising:

i) a solution of said at least one alpha-emitting radioisotope and at least one daughter isotope;
ii) at least one ligand;
ii) a specific binding moiety;
iii) at least one selective binder for said at least one daughter isotope.

wherein said alpha-emitting radioisotope is complexed or complexable by said ligand which is conjugated or conjugatable to said specific binding moiety.

19) A kit as claimed in claim 18 wherein said solution of said at least one alpha-emitting radioisotope and at least one daughter isotope is present in a first vessel (e.g. vial, syringe etc) and said ligand conjugated to said specific binding moiety is present in a second vessel.

20) A kit as claimed in claim 18 or claim 19 wherein said selective binder is present in the form of at least one filter, such as a syringe filter, through which said solution of alpha-emitting radioisotope can be passed after complexation by said ligand and optionally after conjugation to said specific binding moiety.

21) A kit as claimed in claim 18 or claim 19 wherein said selective binder is present in the form of or attached to at least one solid or gel support.

22) A kit as claimed in claim 21 wherein said selective binder is present in said first vessel.

23) A kit as claimed in any of claims 18 to 22 wherein said selective binder arranged to be separated from said solution by the process of administration of said solution.

24) A kit as claimed in claim 23 wherein said solid or gel support is least one selected from membranes, resin beads, gel beads, self-assembled lipid structures (e.g. liposomes), microparticles, nanoparticles, powders, crystals and polymer structures.

25) A kit as claimed in any of claims 18 to 24 wherein said selective binder comprises at least one selected from cation exchange resins, size exclusion resins, zeolites, molecular sieves, hydroxyapatite, alginates, liposomes, phosphonates, polyphosphonates, phospholipids, glycolipids, lipo-proteins, oligosaccharides, ferritin, transferrin, phytic acid and co-precipitation agents.

26) A kit as claimed in any of claims 18 to 25 wherein said alpha-emitting radioisotope is at least one thorium radioisotope such as ^{227}Th.

27) A kit as claimed in any of claims 18 to 26 wherein said daughter isotope is at least one radium isotope, such as ^{223}Ra.

28) A kit as claimed in any of claims 18 to 27 additionally comprising a filter and/or an administration device.

29) A kit as claimed in any of claims 18 to 28 comprising a filter of pore size of no larger than 0.22 μm

30) An administration device comprising a solution of at least one alpha-emitting radionuclide complex and at least one daughter nuclide, said device further comprising a filter containing at least one selective binder for said daughter nuclide.

31) A device as claimed in claim 30 in the form of a disposable syringe and syringe filter.

32) A kit as claimed in any of claims 18 to 29 comprising an administration device comprising a solution of at least one complexed alpha-emitting radionuclide and at least one daughter nuclide, said kit further comprising a selective binder for said daughter nuclide in the form of a filter.

33) A method for the formation of an injectable solution of an alpha-radionuclide complex comprises the steps of:

a) combining a first solution comprising a dissolved salt of an alpha-emitting radionuclide and at least one daughter nuclide with a second solution comprising at least one ligand conjugated to at least one targeting moiety;

b) Iincubating the combined solutions at a suitable temperature (e.g. 0°C to 50°C, preferably 20°C to 40°C) for a period to allow complex formation between said ligand and said alpha-emitting radioisotope whereby to form a solution of at least one alpha-emitting radioisotope complex;

c) contacting said solution of at least one alpha-emitting radioisotope complex with at least one selective binder for at least one of said daughter nuclides.

d) separating said solution of at least one alpha-emitting radionuclide complex from said at least one selective binder.

34) A method for the formation of an injectable solution as claimed in claim 33 wherein steps c) and d) comprise a method for generating a purified solution as claimed in any of claims 1 to 17.