

DESCRIPTION

DIASTEREOISOMERICALLY ENRICHED COMPLEX OF GADOLINIUM AND OF A PCTA-BASED CHELATING LIGAND, AND PROCESS FOR PREPARING AND PURIFYING SAME

5 The present invention relates to a novel process for preparing and purifying a complex of gadolinium and of a PCTA-based chelating ligand, which makes it possible to obtain preferentially stereoisomers of said complex which have physicochemical properties that are most particularly advantageous for applications as contrast agent in the field of medical imaging, notably for magnetic resonance imaging. The present invention also relates to the
10 diastereoisomerically enriched complex per se, to a composition comprising said complex, and also to a process for preparing the corresponding chelating ligand by decomplexation of said complex, and to the ligand per se.

Many contrast agents based on chelates of lanthanides (paramagnetic metal), in particular gadolinium (Gd), are known, for example described in US 4 647 447. These products are
15 often grouped under the term GBCA (gadolinium-based contrast agent). Several products are marketed, among which are macrocyclic chelates such as meglumine gadoterate based on DOTA (1,4,7,10-tetraazacyclododecane-N,N',N'',N'''-tetraacetic acid), gadobutrol based on DO3A-butrol, gadoteridol based on HPDO3A, and also linear chelates, notably based on DTPA (diethylenetriaminepentaacetic acid) or on DTPA-BMA (gadodiamide
20 ligand).

Other products, some of which are under development, represent a new generation of GBCA. They are essentially complexes of macrocyclic chelates, such as bicyclopolyazamacrocyclocarboxylic acid (EP 0 438 206) or PCTA derivatives (i.e. derivatives comprising *a minima* the 3,6,9,15-tetraazabicyclo[9,3,1]pentadeca-1(15),11,13-
25 triene-3,6,9-triacetic acid chemical structure), as described in EP 1 931 673.

The complexes of PCTA-based chelating ligands described in EP 1 931 673 notably have the advantage of being relatively easy to synthesize chemically and, in addition, of having relaxivity superior to that of the other GBCAs (relaxivity r_1 which may be up to 11-12 mM⁻¹.s⁻¹ in water) currently on the market, this relaxivity corresponding to the efficiency of these
30 products and thus to their contrasting power.

In the body, chelates (or complexes) of lanthanide - and notably of gadolinium - are in a state of chemical equilibrium (characterized by its thermodynamic constant K_{therm}), which may lead to an undesired release of said lanthanide (see equation 1 below):



(equation 1)

Complexation chemical equilibrium between the chelate or ligand (Ch) and the lanthanide (L_n) to give the complex Ch- L_n .

Since 2006, a pathology known as NSF (Nephrogenic Systemic Fibrosis or fibrogenic dermatopathy), has been at least partly linked to the release of free gadolinium into the body.

10 This disease has alerted health authorities with regard to gadolinium-based contrast agents marketed for certain categories of patients.

Strategies were thus put into place to solve in an entirely safe manner the complex problem of patient tolerance and to limit, or even eliminate, the risk of undesired lanthanide release after administration. This problem is all the more difficult to solve since the administration
15 of contrast agents is often repeated, whether during diagnostic examinations or for the adjustment of doses and the monitoring of the efficacy of a therapeutic treatment.

In addition, mention has been made since 2014 of a possible cerebral deposition of gadolinium after repeated administrations of gadolinium-based products, more particularly of linear gadolinium chelates, such a deposition having been sparingly or not at all reported
20 with gadolinium macrocyclic chelates, such as Dotarem®. Consequently, various countries have decided either to withdraw the majority of the linear chelates from the market, or to drastically limit their indications for use, given their stability which is deemed insufficient.

A first strategy for limiting the risk of lanthanide release into the body thus consists in opting for complexes which are distinguished by thermodynamic and/or kinetic stabilities that are
25 as high as possible. The reason for this is that the more stable the complex, the more the amount of lanthanide released over time will be limited.

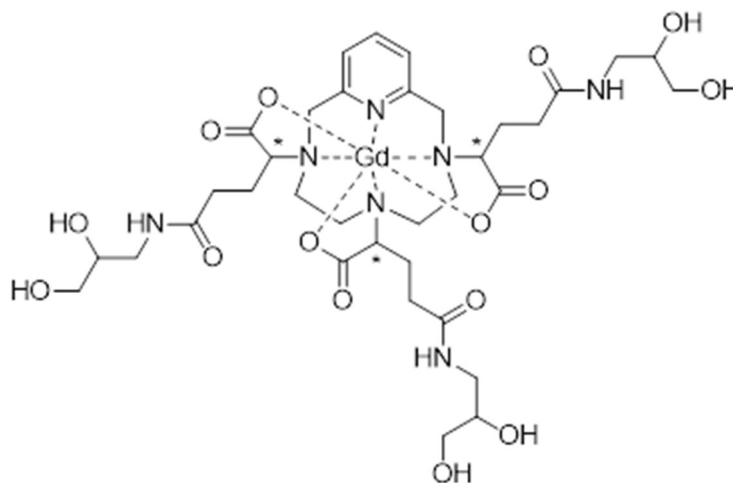
Other approaches for improving the tolerance of chelates of lanthanide (notably of gadolinium) are described in the prior art. US 5 876 695, which is more than 30 years old, reports, for example, formulations comprising, besides the lanthanide chelate, an additional
30 complexing agent, intended for preventing undesired *in-vivo* release of the lanthanide, by complexing the leached lanthanide (Gd^{3+} metal ion). The additional chelating agent may be

introduced into the formulation either in its free form, or in the form of a weak complex, typically of calcium, sodium, zinc or magnesium. While it may, possibly, be distinct from the constituent ligand of the active complex, it is nevertheless important for the complex it forms with the released lanthanide to be less stable than the active complex, so as to prevent a trans-ligation reaction between the active complex and the additional chelate, which would notably have the effect of totally consuming said additional ligand, which could then no longer trap the leached lanthanide. This risk of consumption of the additional chelating agent by trans-ligation is more pronounced when it is added in free form than in the form of a calcium complex, for example.

Thus, in the two strategies described above, it is important for the active complex to be as stable as possible.

However, the complexes of PCTA-based chelating ligands comprising a structure of pyclene type described in EP 1 931 673, while having good kinetic stability, generally have a thermodynamic constant which is lower than that of complexes of the other cyclene-based macrocycles.

This is notably the case for the complex of formula (II) represented below:



(II)

Indeed, as is notably described in WO 2014/174120, the thermodynamic equilibrium constant corresponding to the reaction for the formation of the complex of formula (II), also known as the stability constant, is $10^{14.9}$ (i.e. $\log(K_{\text{therm}}) = 14.9$). For comparative purposes, the stability constant of the gadolinium complex of 1,4,7,10-tetraazacyclododecane-N,N',N'',N'''-tetraacetic acid (DOTA-Gd) is $10^{25.6}$ (i.e. $\log(K_{\text{therm}}) = 25.6$).

It should be noted, however, that the complex of formula (II) corresponds to several stereoisomers, notably due to the presence of the three asymmetric carbon atoms located in the α position on the side chains of the complex, relative to the nitrogen atoms of the macrocycle onto which said side chains are grafted. These three asymmetric carbons are marked with an asterisk (*) in formula (II) represented above.

Thus, the synthesis of the complex of formula (II) as described in EP 1 931 673 results in the production of a mixture of stereoisomers.

The aminopropanediol groups of the side chains of the complex of formula (II) also include an asymmetric carbon. Thus, the complex of formula (II) comprises in total six asymmetric carbons, and thus exists in the form of 64 configurational stereoisomers. However, in the rest of the description, the only source of stereoisomerism considered for a given side chain will, for the sake of simplicity, be that corresponding to the asymmetric carbon bearing the carboxylate group, marked with an asterisk (*) in formula (II) represented above.

Since each of these three asymmetric carbons may be of R or S absolute configuration, the complex of formula (II) exists in the form of eight families of stereoisomers, referred to hereinbelow as II-RRR, II-SSS, II-RRS, II-SSR, II-RSS, II-SRR, II-RSR and II-SRS. More precisely, according to the usual nomenclature in stereochemistry, the complex of formula (II) exists in the form of eight families of diastereoisomers.

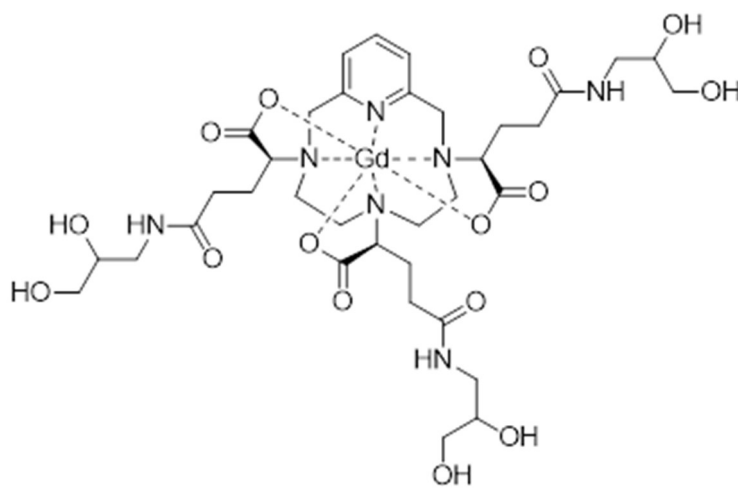
The use of the term "family" is justified in that each of these families includes several stereoisomers, notably due to the presence of an asymmetric carbon within the aminopropanediol group, as mentioned previously.

Nevertheless, since, in the rest of the description, the stereoisomerism associated with the asymmetric carbon of a given aminopropanediol group will not be considered, the terms isomers, stereoisomers or diastereoisomers II-RRR, II-SSS, II-RRS, II-SSR, II-RSS, II-SRR, II-RSR and II-SRS will be used without distinction, without stating that each corresponds to a family of stereoisomers.

The inventors have succeeded in separating and in identifying by high-performance liquid chromatography (HPLC) and by ultra-high-performance liquid chromatography (UHPLC) four unresolved peaks or groups of isomers of the complex of formula (II) obtained according to the process of the prior art, corresponding to four different elution peaks characterized by their retention time on the chromatogram, which will be referred to in the

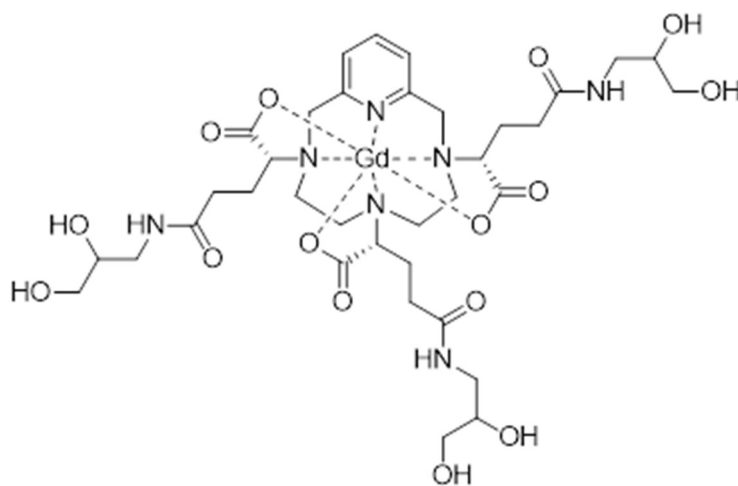
rest of the description as iso1, iso2, iso3 and iso4. By performing the process described in EP 1 931 673, the respective contents of the groups iso1, iso2, iso3 and iso4 in the mixture obtained are as follows: 20%, 20%, 40% and 20%.

5 They then discovered that these various groups of isomers had different physicochemical properties, and determined that the group of isomers known as iso4, which comprises a mixture of the isomers II-RRR and II-SSS of formulae (II-RRR) and (II-SSS) represented below, proves to be the most advantageous as contrast agent for medical imaging.



(II-SSS)

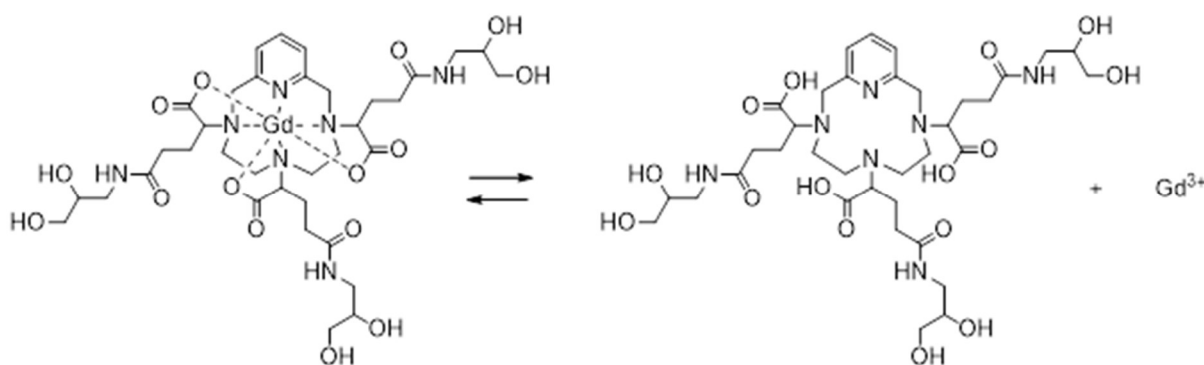
10



(II-RRR)

Indeed, iso4 is distinguished, surprisingly, by a thermodynamic stability that is markedly superior to that of the mixture of diastereoisomers in the form of which the complex of formula (II) is obtained by performing the process described in EP 1 931 673. Specifically, its equilibrium thermodynamic constant $K_{\text{therm iso4}}$ is equal to $10^{18.7}$ (i.e. $\log(K_{\text{therm iso4}}) = 18.7$) this value having been determined by performing the method in Pierrard *et al.*, *Contrast Media Mol. Imaging*, 2008, 3, 243-252 and Moreau *et al.*, *Dalton Trans.*, 2007, 1611-1620.

Besides, iso4 is the group of isomers which has the best kinetic inertia (also known as kinetic stability) among the four groups isolated by the inventors. Specifically, the inventors evaluated the kinetic inertia of the four groups of isomers by studying their decomplexation kinetics in acidic aqueous solution (pH = 1.2), at 37°C. The half-life time values ($T_{1/2}$) which were determined for each of the groups of isomers are indicated in table 1 below, the half-life time corresponding to the time after which 50% of the amount of complex initially present has been dissociated, according to the following decomplexation reaction (equation 2):



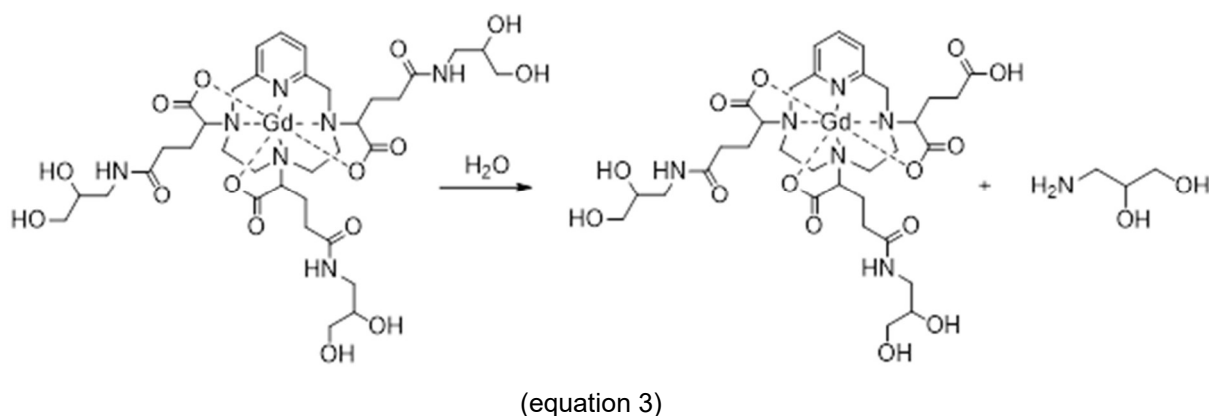
(equation 2)

Groups of isomers	$T_{1/2}$ (pH 1.2 – 37°C)
Iso1	18 hours
Iso2	6 hours
Iso3	8 days
Iso4	27 days

Table 1: decomplexation kinetics for the groups of isomers iso1 to iso4

For comparative purposes, gadobutrol or gadoterate, which are macrocyclic gadolinium complexes, respectively have a kinetic inertia of 18 hours and of 4 days under the same conditions, whereas linear gadolinium complexes such as gadodiamide or gadopentetate dissociate instantaneously.

- 5 In addition, iso4 is chemically more stable than iso3, notably. The reason for this is that the amide functions of the complex of formula (II) are liable to be hydrolysed. The hydrolysis reaction of an amide function (equation 3) results in the formation of a dicoupled impurity, which is accompanied by the release of 3-amino-1,2-propanediol. The inventors studied the kinetics of the hydrolysis reaction of the complex of formula (II) in aqueous solution at
10 pH 13 and observed that the amide functions of iso4 are more stable with respect to hydrolysis than those of iso3.



- As regards the relaxivity of the various groups of isomers, i.e. their efficiency as contrast
15 agent, the measurements taken demonstrate a contrasting power that is relatively equivalent for the groups iso1, iso2 and iso4, and reduced efficiency for iso3 (see table 2).

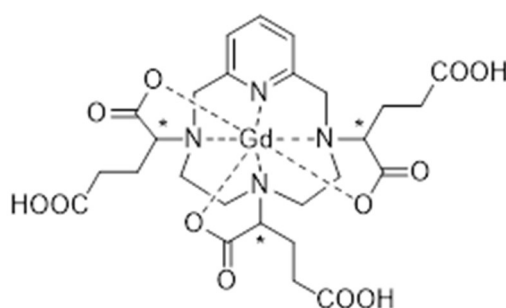
Groups of isomers	r1 20 MHz (mM ⁻¹ .s ⁻¹)	r1 60 MHz (mM ⁻¹ .s ⁻¹)
Iso1	12.6	12.5
Iso2	13.3	12.9
Iso3	8.0	8.1
Iso4	12.9	13.0

Table 2: relaxivity of the groups of isomers iso1 to iso4 at 37°C

- The inventors have succeeded in developing a novel process for preparing and purifying the complex of formula (II), making it possible to obtain preferentially the diastereoisomers
20 II-RRR and II-SSS of said complex, which have particularly advantageous physicochemical properties. The process according to the invention comprises a step of isomeric

enrichment, by conversion of the least stable stereoisomers into the most stable stereoisomers, which, surprisingly, while being performed on the hexaacid intermediate complex and not on the final complex, makes it possible to obtain very predominantly the most stable isomers of the complex of formula (II).

- 5 The implementation of a process which makes it possible to obtain predominantly the diastereoisomers of interest is unquestionably advantageous when compared with the alternative consisting in preparing the mixture of stereoisomers, then subsequently attempting to separate the diastereoisomers according to the usual techniques and thus to isolate the isomers of interest using any separation technique that is well known in the art.
- 10 Indeed, besides the fact that it is easier to perform a process not involving a step of separation of diastereoisomers on an industrial scale, the absence of separation firstly affords considerable time-saving and secondly makes it possible to improve the overall yield of the process, by limiting as much as possible the production of the undesired diastereoisomers which would ultimately be discarded. Moreover, the usual separation
- 15 techniques generally involve an abundant use of solvents, which, beyond the financial cost, is not desirable for environmental reasons. Furthermore, chromatography on silica is in particular to be avoided, given the health risks inherent in professional exposure to silica, which is classified as carcinogenic to humans (group 1) by the International Agency for Research on Cancer.
- 20 As indicated previously, the process for preparing the complex of formula (II) developed by the inventors is based on a step of isomeric enrichment of the intermediate hexaacid gadolinium complex of formula (I) represented below:



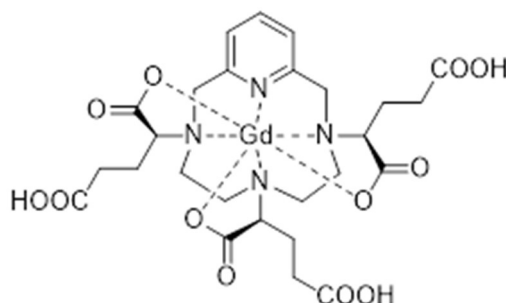
(I)

- 25 The complex of formula (I) corresponds to several stereoisomers, due to the presence of the three asymmetric carbon atoms located in the α position on the side chains of the complex, relative to the nitrogen atoms of the macrocycle onto which said side chains are grafted. These three asymmetric carbons are marked with an asterisk (*) in formula (I) represented above.

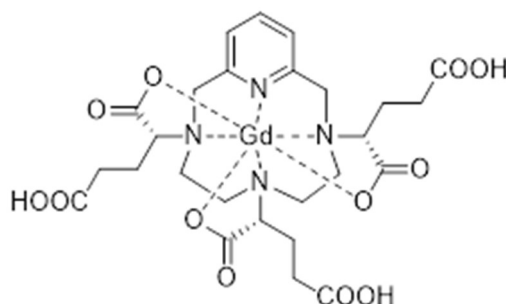
Since each of the three asymmetric carbons bearing a carboxylate function may be of R or S absolute configuration, the complex of formula (I) exists in the form of eight stereoisomers, referred to hereinbelow as I-RRR, I-SSS, I-RRS, I-SSR, I-RSS, I-SRR, I-RSR and I-SRS. More precisely, according to the usual nomenclature in stereochemistry, the complex of formula (I) exists in the form of four pairs of enantiomers, which are mutual diastereoisomers.

The inventors have succeeded in separating and in identifying by high-performance liquid chromatography (HPLC) and by ultra-high-performance liquid chromatography (UHPLC) four unresolved peaks or groups of isomers of the complex of formula (I) obtained according to the process described in EP 1 931 673, corresponding to four different elution peaks characterized by their retention time on the chromatogram, which will be referred to in the rest of the description as isoA, isoB, isoC and isoD.

IsoD crystallizes from water. X-ray diffraction analysis enabled the inventors to determine the crystal structure of this group of isomers, and thus to discover that it comprises the diastereoisomers I-RRR and I-SSS of the complex of formula (I), of formulae (I-RRR) and (I-SSS) represented below.



(I-SSS)



(I-RRR)

It should be noted that the diastereoisomers I-RRR and I-SSS of the complex of formula (I) are enantiomers of each other.

The isomeric enrichment step of the process of the invention aims at enriching the intermediate hexaacid gadolinium complex of formula (I) in isoD.

- 5 The synthesis of the complex of formula (II) notably involves conversion of the carboxylic acid functions of the intermediate hexaacid complex of formula (I) into amide functions. This amidation reaction does not modify the absolute configuration of the three asymmetric carbon atoms of the complex of formula (I).

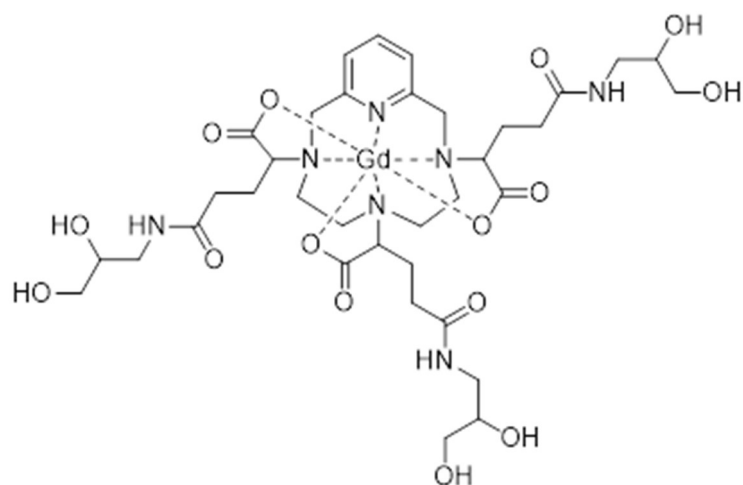
Thus, when the amidation reaction is performed on the hexaacid complex of formula (I) enriched in isoD obtained previously, it makes it possible to obtain the complex of formula (II) enriched in iso4.

Moreover, the purification process developed by the inventors makes it possible, when it is performed following the process for preparing the complex of the abovementioned formula (II), to obtain the complex of formula (II) with an optimized isomeric profile, but also a markedly improved impurity profile.

This diastereoisomerically enriched and purified complex of improved stability can consequently be formulated with a free macrocyclic ligand, such as free DOTA, instead of a calcium complex of DOTA, the use of which was recommended in WO 2014/174120. The use of free DOTA notably has an advantage from an industrial viewpoint, in the sense that it makes it possible to eliminate a step of the process for synthesizing the formulation as described in WO 2014/174120, namely the addition of CaCl_2 .

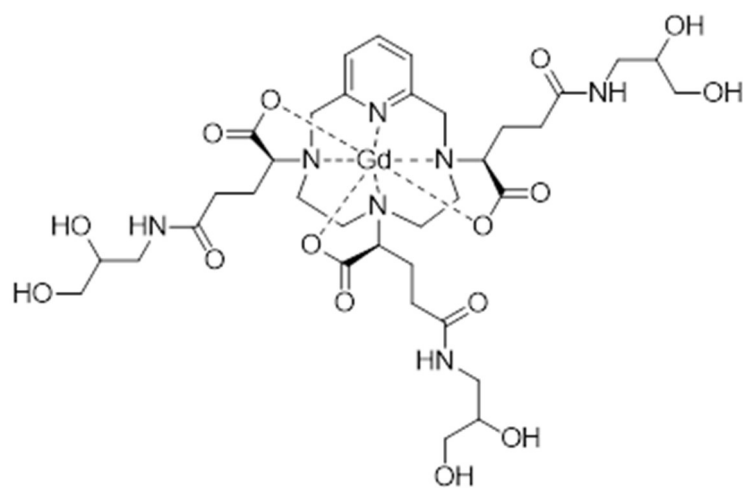
Complex of formula (II)

The present invention thus relates firstly to a complex of formula (II):

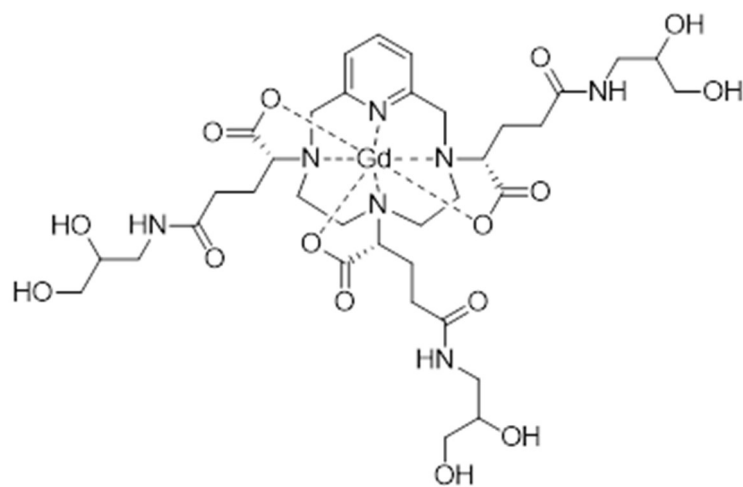


(II)

constituted of at least 80% of a diastereoisomeric excess comprising a mixture of isomers II-RRR and II-SSS of formulae:



(II-SSS)



(II-RRR)

In the context of the present invention, the term "diastereoisomeric excess" is intended to denote, as regards the complex of formula (II), the fact that said complex is predominantly present in the form of an isomer or group of isomers chosen from the diastereoisomers II-RRR, II-SSS, II-RRS, II-SSR, II-RSS, II-SRR, II-RSR and II-SRS. Said diastereoisomeric excess is expressed as a percentage and corresponds to the amount represented by the predominant isomer or group of isomers relative to the total amount of the complex of formula (II). It is understood that this percentage may be on either a molar or mass basis, since isomers have, by definition, the same molar mass.

In one particular embodiment, the complex of formula (II) according to the invention has at least 85%, notably at least 90%, in particular at least 92%, preferably at least 94%, advantageously at least 97%, more advantageously at least 99% of the diastereoisomeric excess comprising the mixture of isomers II-RRR and II-SSS.

Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers II-RRR and II-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers II-RRR and II-SSS.

The term "mixture of isomers II-RRR and II-SSS" also covers, by extension, the case where only one of the isomers, whether it be II-RRR or II-SSS, is present. However, the term "mixture of isomers II-RRR and II-SSS" preferentially denotes all the cases in which each of the isomers II-RRR and II-SSS is present in a variable but non-zero amount.

In a preferred embodiment, the isomers II-RRR and II-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the isomers II-RRR and II-SSS are present in the mixture in a 50/50 ratio.

More particularly, the diastereoisomeric excess as defined previously corresponds to peak 4 in the UHPLC plot (i.e. the fourth unresolved peak of isomers in the order of elution and corresponding to iso4), characterized by a retention time of between 6.0 and 6.6 minutes, typically of about 6.3 minutes, said plot being obtained using the UHPLC method described below.

For the purposes of the present invention, the term "UHPLC plot" means the profile of the concentrations measured by the detector after passage and separation of a mixture of compounds (in this instance of isomers of a compound) on a stationary phase as a function of time for a given composition and a given flow rate of eluent. The UHPLC plot is constituted of various peaks or unresolved peaks characteristic of the compound or of the mixture of compounds analysed.

UHPLC method:

- Waters Cortecs® UPLC T3 150 x 2.1 mm - 1.6 µm column.

It is a reverse-phase UPLC column with spherical particles constituted of a core, which is preferentially very hard, made of silica surrounded by a porous silica with trifunctional C18 (octadecyl) grafting, and the silanols of which have been treated with capping agents (end-capped). It is also characterized by a length of 150 mm, an inside diameter of 2.1 mm, a particle size of 1.6 µm, a porosity of 120 Å and a carbon content of 4.7%.

Preferentially, the stationary phase used should be compatible with the aqueous mobile phases.

- analytical conditions:

Sample	Aqueous solution of the complex of formula (II) at 2.0 mg/mL
Column temperature	40°C
Sample temperature	Room temperature (20-25°C)
Flow rate	0.3 mL/min
Injection volume	1 µL
UV detection	200 nm

- mobile phase gradient (% v/v):

Time (min)	acetonitrile (100%)	H ₂ SO ₄ (aqueous solution at 0.0005% v/v)
0	1	99
3	5	95
12	10	90

Composition comprising the complex of formula (II)

The present invention relates secondly to a composition comprising:

- the complex of formula (II) constituted of at least 80% of a diastereoisomeric excess comprising a mixture of isomers II-RRR and II-SSS and
- a free macrocyclic ligand.

5 In the present description, the terms "macrocyclic ligand" or "macrocyclic chelate" may be used without distinction.

In the context of the present invention, the term "macrocycle" denotes a ring typically including at least nine atoms, whether they are carbon atoms or heteroatoms, and the term "macrocyclic ligand" or "macrocyclic chelate" is a polydentate, at least bidentate, ligand.

10 For the purposes of the present invention, the term "free macrocyclic ligand" means the macrocyclic ligand in free form, i.e. not complexed, in particular with metals - including lanthanides and actinides - or with alkaline-earth metal cations such as calcium or magnesium. In particular, the free macrocyclic ligand is not in the form of a complex with gadolinium, and is not introduced into the composition in the form of a weak complex, typically of calcium, sodium, zinc or magnesium, as described in US 5 876 695, the
15 presence of said cations in trace amount in the composition and thus of the corresponding complexes not, however, being excluded.

As discussed previously, the formulation of the complex of formula (II) with a free macrocyclic ligand, and not a weak complex of said macrocyclic ligand as recommended in EP 1 931 673, is made possible by the improved stability of the diastereoisomerically
20 enriched complex of formula (II) according to the invention.

In a preferred embodiment, the complex of formula (II) present in the composition of the invention has at least 85%, notably at least 90%, in particular at least 92%, more particularly at least 94%, preferably at least 97%, advantageously at least 99% of the diastereoisomeric excess comprising the mixture of isomers II-RRR and II-SSS.

25 Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers II-RRR and II-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers II-RRR and II-SSS.

The term "mixture of isomers II-RRR and II-SSS" also covers, by extension, the case where only one of the isomers, whether it be II-RRR or II-SSS, is present. However, the term "mixture of isomers II-RRR and II-SSS" preferentially denotes all the cases in which each of the isomers II-RRR and II-SSS is present in a variable but non-zero amount.

- 5 In a preferred embodiment, the isomers II-RRR and II-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the isomers II-RRR and II-SSS are present in the mixture in a 50/50 ratio.

- 10 In one advantageous embodiment, the composition according to the invention has a concentration of free gadolinium of less than 1 ppm (m/v), preferentially less than 0.5 ppm (m/v).

- 15 In the present description, unless otherwise mentioned, the terms "Gd", "gadolinium" and "Gd³⁺" are used without distinction to denote the Gd³⁺ ion. By extension, it may also be a source of free gadolinium, such as gadolinium chloride (GdCl₃) or gadolinium oxide (Gd₂O₃).

In the present invention, the term "free Gd" denotes the non-complexed forms of gadolinium, which are preferably available for complexation. It is typically the Gd³⁺ ion dissolved in water. By extension, it may also be a source of free gadolinium, such as gadolinium chloride (GdCl₃) or gadolinium oxide (Gd₂O₃).

- 20 Gadolinium in free form is typically measured by colorimetric assay, generally xylenol orange or Arsenazo (III). In the absence of a metal ion (such as gadolinium), these indicators have a specific colour: at acidic pH, xylenol orange is yellow, whereas Arsenazo is pink. In the presence of gadolinium, their colour changes to violet.

- 25 Visual determination of the colour change of the solution makes it possible to verify the presence or absence of gadolinium in the solution.

- 30 Moreover, it is possible to quantitatively measure the free gadolinium that is in the solution via a back titration, for example using EDTA as "weak" gadolinium chelate. In such an assay, the coloured indicator is added until a violet colour is obtained. EDTA, a gadolinium ligand, is then added dropwise to the mixture. Since EDTA is a stronger complexing agent than the coloured indicator, the gadolinium changes ligand and leaves the coloured

indicator to become preferentially complexed with EDTA. The coloured indicator thus gradually regains its non-complexed form.

When the amount of EDTA added is equal to the initial amount of free Gd, the coloured indicator is entirely in its free form and the solution "turns" yellow. Since the amount of EDTA added is known, this makes it possible to know the initial amount of free Gd in the solution to be assayed.

These methods are well known to those skilled in the art and are notably described in Barge *et al.* (*Contrast Media and Molecular Imaging* 1, 2006, 184-188).

These colorimetric methods are thus usually performed on a solution whose pH is between 4 and 8. The reason for this is that outside these pH ranges, the accuracy of the measurement may be affected due to a modification (or even suppression) of the colour change.

Thus, if need be, the pH of the sample to be assayed is adjusted to be between 4 and 8. Notably, if the pH of the sample is acidic, and in particular less than 4, the pH is advantageously adjusted by adding a base, and the measurement of the free Gd is then performed on the sample at the adjusted pH.

The composition according to the invention thus has stability over time, i.e. its composition remains in accordance with the specifications in terms of concentration of free gadolinium (in particular its concentration of free Gd remains less than 1 ppm (m/v)), over a period of at least 3 years, preferentially of at least 4 years or more preferentially of at least 5 years, notably in terms of content of free paramagnetic metal. According to the ICH guidelines, observation of this stability for six months at 40°C is considered as a good indication of stability for 3 years at 25°C.

In one particular embodiment, the composition according to the invention has a concentration of between 0.01 and 1.5 mol.L⁻¹, preferentially between 0.2 and 0.7 mol.L⁻¹, more preferentially between 0.3 and 0.6 mol.L⁻¹ of complex of formula (II) described above.

The complex of formula (II) is assayed via the methods known to those skilled in the art. It may notably be assayed after mineralization and assay of the total gadolinium present in the composition, by atomic emission spectrometry (also known as ICP-AES or ICP Atomic Emission Spectrometry).

The content of complex of formula (II) allows this composition to have an optimum contrasting power while at the same time having a satisfactory viscosity. Specifically, below 0.01 mol.L⁻¹ of complex of formula (II) described above, the performance qualities as a contrast product are less satisfactory, and at a concentration above 1.5 mol.L⁻¹, the viscosity of this composition becomes too great for easy handling.

In one particular embodiment, the composition according to the invention comprises between 0.002 and 0.4 mol/mol%, notably between 0.01 and 0.3 mol/mol%, preferably between 0.02 and 0.2 mol/mol% and more preferentially between 0.05 and 0.15 mol/mol% of free macrocyclic ligand relative to the complex of formula (II).

Advantageously, the macrocyclic ligand is selected from the group constituted of DOTA, NOTA, DO3A, BT-DO3A, HP-DO3A, PCTA, DOTA-GA and derivatives thereof.

Preferably, it is DOTA (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid).

The concentration of free DOTA in the composition is typically measured by back titration with copper, for example using copper sulfate as source of copper ions.

In this method, which is well known to those skilled in the art, a solution containing a known initial concentration Q_0 of copper sulfate is preferentially used, this concentration being greater than the amount of free ligand in the solution. The solution to be assayed, containing free DOTA in an amount Q_1 to be determined, is added to this copper sulfate solution. DOTA is a very good copper complexing agent: the formation of a DOTA-copper complex is thus observed.

Back titration of the copper remaining free in the solution is then advantageously performed by potentiometry. To do this, EDTA is, for example, added dropwise to the mixture. The EDTA complexes the free copper in solution without, however, decomplexing the DOTA-copper, since DOTA is a stronger complexing agent than EDTA. When the amount of EDTA added Q_2 is equal to the amount of free copper in solution, a sudden drop in the potential of the solution is observed.

Knowing the initial amount of copper Q_0 and the amount of EDTA added Q_2 , subtraction of these two values $Q_0 - Q_2$ gives the amount of free DOTA in the solution to be assayed Q_1 .

Alternatively, HPLC methods may be used, notably the HILIC LC-UV method.

These measuring methods (in particular the potentiometric methods) are performed on solutions whose pH is advantageously between 4 and 8. Thus, if need be, the pH of the sample to be assayed is adjusted to be between 4 and 8. Notably, if the pH of the sample is acidic, and in particular less than 4, the pH is advantageously adjusted by adding a base
 5 such as meglumine, and the measurement of the free DOTA is then performed on the sample at the adjusted pH.

Preferentially, the proportions specified in the present invention and in particular above are proportions before sterilization of the composition.

Advantageously, the pH of the composition is between 4.5 and 8.5, preferentially between
 10 5 and 8, advantageously between 6 and 8, notably between 6.5 and 8. These pH ranges notably make it possible to limit the appearance of certain impurities and to promote the complexation of the paramagnetic metal ion M.

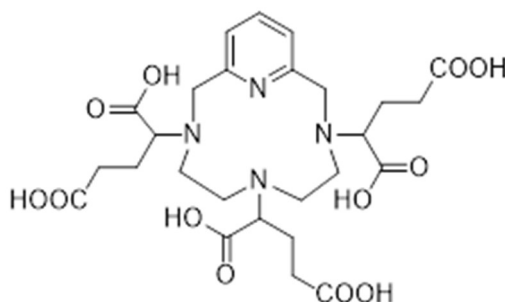
In particular, the composition according to the invention may be buffered, i.e. it may also comprise a buffer chosen from common buffers established for the pH range 5 to 8,
 15 preferentially among lactate, tartrate, malate, maleate, succinate, ascorbate, carbonate, Tris (Tris(hydroxymethyl)aminomethane), HEPES (2-[4-(2-hydroxyethyl)-1-piperazine]ethanesulfonic acid) and MES (2-morpholinoethanesulfonic acid) buffers and mixtures thereof, and preferentially a buffer chosen from Tris, lactate, tartrate, carbonate and MES buffers and mixtures thereof. Advantageously, the composition according to the
 20 invention comprises the Tris buffer.

The composition that is the subject of the invention is preferentially sterile.

Process for preparing the complex of formula (II)

The present invention also relates to a process for preparing the complex of formula (II), comprising the following successive steps:

25 **a)** Complexation of the hexaacid of formula (III) below:



(III)

with gadolinium to obtain the hexaacid gadolinium complex of formula (I) as defined previously,

- 5 **b)** Isomerization by heating the hexaacid gadolinium complex of formula (I) in an aqueous solution at a pH of between 2 and 4, to obtain a diastereoisomerically enriched complex constituted of at least 80% of a diastereoisomeric excess comprising a mixture of the isomers I-RRR and I-SSS of said hexaacid gadolinium complex of formula (I), and
- 10 **c)** Formation, starting with the diastereoisomerically enriched complex obtained in step b), of the complex of formula (II), by reaction with 3-amino-1,2-propanediol.

In the present description, unless otherwise mentioned, the terms "Gd", "gadolinium" and "Gd³⁺" are used without distinction to denote the Gd³⁺ ion. By extension, it may also be a source of free gadolinium, such as gadolinium chloride (GdCl₃) or gadolinium oxide (Gd₂O₃).

- 15 In the present invention, the term "free Gd" denotes the non-complexed forms of gadolinium, which are preferably available for complexation. It is typically the Gd³⁺ ion dissolved in water. By extension, it may also be a source of free gadolinium, such as gadolinium chloride (GdCl₃) or gadolinium oxide.

▪ **Step a)**

- 20 In this step, a complexation reaction takes place between the hexaacid of formula (III) and gadolinium, which makes it possible to obtain the hexaacid gadolinium complex of formula (I) as defined previously.

According to a particular embodiment, step a) comprises the reaction between the hexaacid of formula (III) and a source of free Gd in water.

- 25 In a preferred embodiment, the source of free Gd is GdCl₃ or Gd₂O₃, preferably Gd₂O₃.

Preferably, the reagents used in step a), i.e. the source of gadolinium (typically gadolinium oxide), the hexaacid of formula (III) and water, are as pure as possible, notably as regards the metal impurities.

Thus, the source of gadolinium will advantageously be gadolinium oxide, preferably with a purity of greater than 99.99% and even more preferably greater than 99.999%.

The water used in the process preferably comprises less than 50 ppm of calcium, more preferably less than 20 ppm and most preferably less than 15 ppm of calcium. Generally, the water used in the process is deionized water, water for injection (injection-grade water) or purified water.

Advantageously, the amounts of the reagents (the hexaacid of formula (III) and gadolinium) used in this step a) correspond to, or are close to, stoichiometric proportions, as dictated by the balance equation of the complexation reaction which takes place during this step.

The term "close to stoichiometric proportions" means that the difference between the molar proportions in which the reagents are introduced and the stoichiometric proportions is less than 15%, notably less than 10%, preferably less than 8%.

Gadolinium may notably be introduced in slight excess relative to the stoichiometric proportions. The ratio of the amount of material introduced as gadolinium to the amount of material introduced as hexaacid of formula (III) is then greater than 1, but typically less than 1.15, notably less than 1.10, advantageously less than 1.08. In other words, the amount of gadolinium introduced is greater than 1 equivalent (eq.), but typically less than 1.15 eq., notably less than 1.10 eq., advantageously less than 1.08 eq., relative to the amount of hexaacid of formula (III) introduced, which itself corresponds to 1 equivalent. In the preferred embodiment in which the source of free gadolinium is Gd_2O_3 , the amount of Gd_2O_3 introduced is then typically greater than 0.5 eq., but less than 0.575 eq., notably less than 0.55 eq., advantageously less than 0.54 eq., relative to the amount of hexaacid of formula (III) introduced (1 eq.).

According to a particular embodiment, step a) comprises the following successive steps:

a1) Preparation of an aqueous solution of hexaacid of formula (III), and

a2) Addition, to the aqueous solution obtained in step a1), of a source of free gadolinium.

In this embodiment, the content of hexaacid of formula (III) in the aqueous solution prepared in step a1) is typically between 10% and 60%, notably between 15% and 45%,

preferably between 20% and 35%, advantageously between 25% and 35% and even more advantageously between 25% and 30% by weight relative to the total weight of the aqueous solution.

Preferentially, steps a) and b) are performed according to a one-pot embodiment, i.e. in the same reactor and without an intermediate step of isolation or purification.

Thus, in this preferred embodiment, the hexaacid gadolinium complex of formula (I) formed in step a) is directly subjected to the isomerization step b) without being isolated or purified, and in the same reactor as that used for step a).

10 ▪ Step b)

The hexaacid gadolinium complex of formula (I) formed by the complexation reaction between the hexaacid of formula (III) and gadolinium in step a) is initially obtained in the form of a mixture of diastereoisomers.

Step b) aims at enriching the mixture of diastereoisomers in the isomers I-RRR and I-SSS, to obtain the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) constituted of at least 85%, notably of at least 90%, in particular of at least 95%, preferably of at least 97%, advantageously of at least 98%, more advantageously of at least 99% of a diastereoisomeric excess comprising the mixture of the isomers I-RRR and I-SSS.

In the context of the present invention, the term "diastereoisomeric excess" is intended to denote, as regards the hexaacid gadolinium complex of formula (I), the fact that said complex is predominantly present in the form of an isomer or group of isomers chosen from the diastereoisomers I-RRR, I-SSS, I-RRS, I-SSR, I-RSS, I-SRR, I-RSR and I-SRS. Said diastereoisomeric excess is expressed as a percentage and corresponds to the amount represented by the predominant isomer or group of isomers relative to the total amount of the hexaacid gadolinium complex of formula (I). It is understood that this percentage may be on either a molar or mass basis, since isomers have, by definition, the same molar mass.

Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers I-RRR and I-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers I-RRR and I-SSS.

The inventors have in fact discovered that factors such as the pH and the temperature of the solution of hexaacid gadolinium complex of formula (I) obtained on conclusion of step a) have an influence on the ratio in which the various isomers of the complex of formula (I) are present in the mixture of diastereoisomers. Over time, the mixture tends to become enriched in a group of isomers comprising the isomers which are, surprisingly, the most thermodynamically stable but also the most chemically stable, in this instance the isomers I-RRR and I-SSS.

- 10 The term "mixture of isomers I-RRR and I-SSS" also covers, by extension, the case where only one of the isomers, whether it be I-RRR or I-SSS, is present.

However, in a preferred embodiment, the isomers I-RRR and I-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the mixture of isomers I-RRR/I-SSS is a racemic (50/50) mixture.

Step b) of isomerization of the hexaacid gadolinium complex of formula (I) in an aqueous solution is typically performed at a pH of between 2 and 4, notably between 2 and 3, advantageously between 2.2 and 2.8.

The pH is preferentially adjusted with an acid, preferably an inorganic acid, such as hydrochloric acid, hydrobromic acid, sulfuric acid, nitric acid or phosphoric acid, for example with hydrochloric acid.

It is entirely surprising that, under such pH conditions, enrichment of the mixture in particular isomers, in this instance the isomers I-RRR and I-SSS, takes place, since it is known in the art that gadolinium chelates are characterized by low kinetic inertia in acidic medium. Indeed, the higher the concentration of H⁺ ions in the medium, the greater the probability that a proton is transferred onto one of the donor atoms of the ligand, thus bringing about dissociation of the complex. Consequently, a person skilled in the art would have expected that placing the hexaacid gadolinium complex of formula (I) in an aqueous solution at a pH of between 2 and 4 would bring about dissociation of said complex, rather than its isomerization into I-RRR and I-SSS.

It should be noted that the pH range recommended by EP 1 931 673 for the complexation of the hexaacid of formula (III), namely 5.0-6.5, does not make it possible to obtain the complex of formula (I) enriched in its isomers I-RRR and I-SSS.

5 Step b) is typically performed at a temperature of between 80°C and 130°C, notably between 90°C and 125°C, preferably between 98°C and 122°C, advantageously between 100°C and 120°C, typically for a time of between 10 hours and 72 hours, notably between 10 hours and 60 hours, advantageously between 12 hours and 48 hours.

Contrary to all expectations, such temperature conditions, which, combined with the abovementioned pH conditions, should favour the instability of the gadolinium chelate, do
10 not result in its decomplexation or in the formation of any other impurity, but in its isomerization into I-RRR and I-SSS.

In one particular embodiment, the aqueous solution of step b) comprises acetic acid. Step b) is then advantageously performed at a temperature of between 100°C and 120°C, notably between 110°C and 118°C, typically for a time of between 12 hours and 48 hours,
15 notably between 20 hours and 30 hours, in particular between 24 hours and 26 hours.

The acetic acid is preferably added before the heating of the solution of hexaacid gadolinium complex of formula (I) obtained in step a) in an amount such that the acetic acid content is between 25% and 75%, notably between 40% and 50% by mass relative to the mass of hexaacid of formula (III) used in step a).

20 When the aqueous solution is heated to a temperature advantageously between 100°C and 120°C, typically between 110°C and 118°C, acetic acid is added gradually as the water evaporates, so as to maintain a constant volume of solution.

According to a preferred embodiment, on conclusion of step b), the diastereoisomerically enriched complex is isolated by crystallization, preferably by crystallization by seeding.

25 In this embodiment, step b) comprises the following successive steps:

b1) Isomerization by heating the hexaacid gadolinium complex of formula (I) in an aqueous solution at a pH of between 2 and 4 to obtain a diastereoisomerically enriched complex constituted of at least 80% of the diastereoisomeric excess comprising the mixture of the isomers I-RRR and I-SSS of said hexaacid gadolinium
30 complex of formula (I), and

b2) Isolation by crystallization of said diastereoisomerically enriched complex, preferably by crystallization by seeding.

The crystallization step b2) aims firstly at removing any impurities present in the aqueous solution, which may result from previous steps, so as to obtain a decolourized product of higher purity, in the form of crystals, and secondly at continuing the diastereoisomeric enrichment of the hexaacid gadolinium complex of formula (I), so as to obtain a diastereoisomeric excess comprising the mixture of the isomers I-RRR and I-SSS of said complex which is higher than that obtained on conclusion of step b1). Indeed, the isomers I-RRR and I-SSS of the hexaacid complex of formula (I) crystallize from water. On the other hand, the hexaacid gadolinium complex of formula (I) not enriched in said isomers does not crystallize.

The fact that the isomers I-RRR and I-SSS, in which the complex tends to become enriched in the course of step b) (and, contrary to all expectations, in the light of the conditions under which it is performed), are the only isomers of the complex to crystallize from water is an entirely unexpected result. The isomerization and crystallization thus contribute synergistically towards the enrichment in isomers I-RRR and I-SSS and consequently towards the overall efficiency of the process according to the invention.

Moreover, it should be noted that crystallization from water of the isomers of interest of the hexaacid gadolinium complex of formula (I) makes it possible to avoid an addition of solvent as described in Example 7 of EP 1 931 673, which involves a step of precipitation from ethanol of the trisodium salt of said complex.

Step b2) is advantageously performed at a temperature of between 10°C and 70°C, notably between 30°C and 65°C, in particular between 35°C and 60°C.

According to one variant, after lowering the temperature of the aqueous solution, so that it is within the ranges indicated above, the crystallization process is induced by seeding. "Crystallization by seeding", also known as "crystallization by priming", comprises the introduction into the reactor in which the crystallization is performed (also known as the crystallization vessel) of a known amount of crystals, known as "seed" or "primer". This makes it possible to reduce the crystallization time. Crystallization by seeding is well known to those skilled in the art. In the process according to the invention, seeding using a primer, in the present instance crystals of diastereoisomerically enriched hexaacid gadolinium complex of formula (I) added to the aqueous solution of the diastereoisomerically enriched

complex whose temperature has been lowered beforehand, makes it possible to obtain nucleation, and thus to initiate the crystallization. The duration of the crystallization by seeding is advantageously between 2 hours and 20 hours and preferably between 6 hours and 18 hours; typically, it is 16 hours.

- 5 The crystals of diastereoisomerically enriched hexaacid gadolinium complex of formula (I) are then typically isolated by filtration and drying, by means of any technique well known to those skilled in the art.

Advantageously, the degree of purity of the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) isolated on conclusion of step b2) is greater than 95%,
 10 notably greater than 98%, advantageously greater than 99%, said degree of purity being expressed as a mass percentage of the complex of formula (I) relative to the total mass obtained on conclusion of step b2).

In a particular embodiment, the diastereoisomerically enriched complex from step b) isolated by crystallization is again purified by recrystallization, to obtain a
 15 diastereoisomerically enriched and purified complex.

In this embodiment, step b) comprises, besides the successive steps b1) and b2) described previously, a step **b3)** of purification by recrystallization of the isolated diastereoisomerically enriched hexaacid gadolinium complex of formula (I).

The recrystallization step b3) aims, like the crystallization step b2), firstly at obtaining a
 20 product of higher purity, and secondly at continuing the diastereoisomeric enrichment of the hexaacid gadolinium complex of formula (I), so as to obtain a diastereoisomeric excess comprising the mixture of the isomers I-RRR and I-SSS of said complex which is higher than that obtained on conclusion of step b2).

Step b3) typically comprises the following successive substeps:

- 25
- suspension of the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) isolated in step b2) in aqueous solution, preferably in water,
 - dissolution of said complex by heating to a temperature advantageously between 80°C and 120°C, for example to 100°C,
 - recrystallization, preferably by seeding, at a temperature advantageously between
- 30 10°C and 90°C, notably between 20°C and 87°C, in particular between 55°C and 85°C,

typically for a time of between 2 hours and 20 hours, notably between 6 hours and 18 hours, and

- isolation of the crystals of diastereoisomerically enriched and purified hexaacid gadolinium complex of formula (I), for example by filtration and drying.

5 The degree of purity of the purified diastereoisomerically enriched hexaacid gadolinium complex of formula (I) isolated on conclusion of step b3) is typically greater than 98%, notably greater than 99%, advantageously greater than 99.5%, said degree of purity being expressed as a mass percentage of the complex of formula (I) relative to the total mass obtained on conclusion of step b2).

10 In another embodiment, the diastereoisomerically enriched complex from step b) is further enriched by selective decomplexation of the diastereoisomers of the complex of formula (I) other than the diastereoisomers I-RRR and I-SSS, *i.e.* by selective decomplexation of the diastereoisomers I-RSS, I-SRR, I-RSR, I-SRS, I-RRS and I-SSR.

15 In this embodiment, step b) comprises, besides the successive steps b1) and b2) described previously, a step **b4)** of selective decomplexation of the diastereoisomers of the complex of formula (I) other than the diastereoisomers I-RRR and I-SSS. In this variant, step b) may also comprise step b3) described previously, said step b3) being performed between steps b2) and b4), or after b4).

20 The selective decomplexation step b4) is directed towards continuing the diastereoisomeric enrichment of the hexaacid gadolinium complex of formula (I), so as to obtain a diastereoisomeric excess comprising the mixture of the isomers I-RRR and I-SSS of said complex which is higher than that obtained on conclusion of step b2) or on conclusion of step b3), when said step is performed prior to step b4).

Step b4) typically comprises the following successive substeps:

- 25
- suspension of the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) isolated in step b2) or in step b3) in water,
 - addition of a base, for example sodium hydroxide,
 - heating to a temperature advantageously between 30°C and 60°C, notably between 35°C and 55°C, for example at 40°C, typically for a time of between 2 hours and 20
- 30
- cooling to a temperature advantageously between 10°C and 30°C, for example to 30°C, and

- isolation of the diastereoisomerically enriched and purified hexaacid gadolinium complex of formula (I), for example by filtration and drying.

Step b4) is made possible by the fact that the isomers I-RRR and I-SSS are the most stable in basic medium. Such basic conditions promote the formation of gadolinium hydroxide, and consequently the decomplexation of the least stable isomers. Thus, it should be noted that, surprisingly, the isomers I-RRR and I-SSS are more stable both in acidic medium, which allows the isomerization step b1), and in basic medium, which allows the selective decomplexation step b4).

In a preferred embodiment, the diastereoisomerically enriched complex obtained on conclusion of step b) according to any one of the variants described above has at least 85%, notably at least 90%, in particular at least 95%, preferably at least 97%, advantageously at least 98%, more advantageously at least 99% of the diastereoisomeric excess comprising the mixture of isomers I-RRR and I-SSS.

Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers I-RRR and I-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers I-RRR and I-SSS.

The term "mixture of isomers I-RRR and I-SSS" also covers, by extension, the case where only one of the isomers, whether it be I-RRR or I-SSS, is present. However, the term "mixture of isomers I-RRR and I-SSS" preferentially denotes all the cases in which each of the isomers I-RRR and I-SSS is present in a variable but non-zero amount.

In a preferred embodiment, the isomers I-RRR and I-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the mixture of isomers I-RRR/I-SSS is a racemic (50/50) mixture.

▪ Step c)

Step c) aims at forming the complex of formula (II) from its precursor, the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) obtained in step b).

During this step, the three carboxylic acid functions of the hexaacid complex of formula (I) borne by the carbon atoms located in the γ position on the side chains of the complex, relative to the nitrogen atoms of the macrocycle on which said side chains are grafted, are converted into amide functions, via an amidation reaction with 3-amino-1,2-propanediol, in racemic or enantiomerically pure form, preferably in racemic form.

This amidation reaction does not modify the absolute configuration of the three asymmetric carbon atoms located in the α position on the side chains, relative to the nitrogen atoms of the macrocycle onto which said side chains are grafted. Consequently, step c) makes it possible to obtain the complex of formula (II) with a diastereoisomeric excess comprising a mixture of the isomers II-RRR and II-SSS that is identical to the diastereoisomeric excess comprising a mixture of the isomers I-RRR and I-SSS with which is obtained the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) obtained on conclusion of step b), which is at least 80%.

In a preferred embodiment, the complex of formula (II) obtained on conclusion of step c) has at least 85%, notably at least 90%, in particular at least 92%, preferably at least 94%, advantageously at least 97%, more advantageously at least 99% of the diastereoisomeric excess comprising the mixture of isomers II-RRR and II-SSS.

Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers II-RRR and II-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers II-RRR and II-SSS.

The term "mixture of isomers II-RRR and II-SSS" also covers, by extension, the case where only one of the isomers, whether it be II-RRR or II-SSS, is present. However, the term "mixture of isomers II-RRR and II-SSS" preferentially denotes all the cases in which each of the isomers II-RRR and II-SSS is present in a variable but non-zero amount.

In a preferred embodiment, the isomers II-RRR and II-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the isomers II-RRR and II-SSS are present in the mixture in a 50/50 ratio.

The amidation reaction may be performed according to any method that is well known to those skilled in the art, notably in the presence of an agent for activating carboxylic acid functions and/or by acid catalysis.

5 It may notably be performed according to the methods described in EP 1 931 673, notably in paragraph [0027] of said patent.

In one particular embodiment, step c) comprises the activation of the carboxylic acid (-COOH) functions of the hexaacid complex of formula (I) borne by the carbon atoms located in the γ position on the side chains of the complex, relative to the nitrogen atoms of the macrocycle on which said side chains are grafted, in the form of functional derivatives
 10 including a carbonyl (C=O) group, which are such that the carbon atom of the carbonyl group is more electrophilic than the carbon atom of the carbonyl group of the carboxylic acid functions. Thus, according to this particular embodiment, said carboxylic acid functions may notably be activated in the form of ester, acyl chloride or acid anhydride functions, or in any activated form that can lead to an amide bond. The activated forms that can lead to
 15 an amide bond are well known to those skilled in the art and may be obtained, for example, by the set of methods known in peptide chemistry for creating a peptide bond. Examples of such methods are given in the publication *Synthesis of peptides and peptidomimetics* volume E22a, pages 425-588, Houben-Weyl *et al.*, Goodman Editor, Thieme-Stuttgart-New York (2004), and, among these examples, mention may be made notably of the methods
 20 of activation of carboxylic acids via an azide (acyl azide), for example via the action of a reagent such as diphenylphosphoryl azide (commonly referred to by the abbreviation DPPA), the use of carbodiimides alone or in the presence of catalysts (for example N-hydroxysuccinimide and derivatives thereof), the use of a carbonyldiimidazole (1,1'-carbonyldiimidazole, CDI), the use of phosphonium salts such as benzotriazol-1-
 25 yloxytris(dimethylamino)phosphonium hexafluorophosphate (commonly referred to by the abbreviation BOP), or else uroniums such as 2-(1H-benzotriazol-1-yl)-1,1,3,3-tetramethyluronium hexafluorophosphate (commonly referred to by the abbreviation HBTU).

Preferably, step c) comprises the activation of the abovementioned carboxylic acid (-COOH) functions in the form of ester, acyl chloride or acid anhydride functions.
 30

This embodiment is preferred to peptide coupling by activation of the carboxylic acid function using a coupling agent such as EDCI/HOBT as described in EP 1 931 673. Indeed, such coupling leads to the formation of one equivalent of 1-ethyl-3-[3-

(dimethylamino)propyl]urea, which must be removed, notably by chromatography on silica or by liquid/liquid extraction by adding a solvent. Independently of the increased complexity of the process caused by such an additional step, the use of such purification methods is not desirable, as discussed previously. Furthermore, the use of HOBT is in itself
 5 problematic, since it is an explosive product.

For the purposes of the present invention, the term "ester function" is intended to denote a -C(O)O- group. It may in particular be a group -C(O)O-R₁, in which R₁ corresponds to a (C₁-C₆)alkyl group.

For the purposes of the present invention, the term "(C₁-C₆)alkyl group" means a linear or
 10 branched, saturated hydrocarbon-based chain containing 1 to 6 and preferably 1 to 4 carbon atoms. Examples that may be mentioned include methyl, ethyl, propyl, isopropyl, butyl, isobutyl, *sec*-butyl, *tert*-butyl, pentyl and hexyl groups.

For the purposes of the present invention, the term "acyl chloride function", also known as "acid chloride function" is intended to denote a -CO-Cl group.

15 For the purposes of the present invention, the term "acid anhydride function" is intended to denote a -CO-O-CO- group. It may in particular be a group -CO-O-CO-R₂, in which R₂ corresponds to a (C₁-C₆)alkyl group.

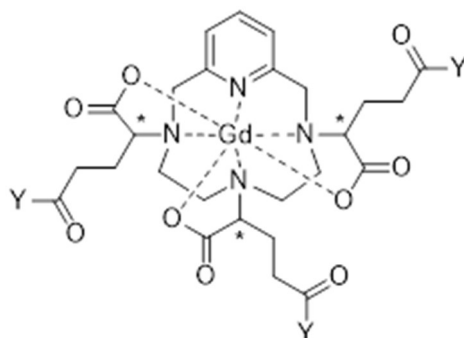
The reactions for converting a carboxylic acid function into an ester, acyl chloride or acid anhydride function are well known to a person skilled in the art, who will be able to perform
 20 them according to any usual method with which he is familiar.

The complex of formula (II) is then obtained by aminolysis of the carboxylic acid functions activated in the form of ester, acyl chloride or acid anhydride functions, notably esters or acid anhydrides, preferably esters, by reaction with 3-amino-1,2-propanediol, in racemic or enantiomerically pure form, preferably in racemic form.

25 Preferentially, the steps of activating the carboxylic acid functions and of aminolysis are performed according to a one-pot embodiment, i.e. in the same reactor and without an intermediate step of isolation or purification of the intermediate including the carboxylic acid functions activated in the form of ester, acyl chloride or acid anhydride functions, notably esters or acid anhydrides, preferably esters.

30 According to a particular embodiment, step c) comprises the following successive steps:

c1) formation of an activated complex of formula (VII),

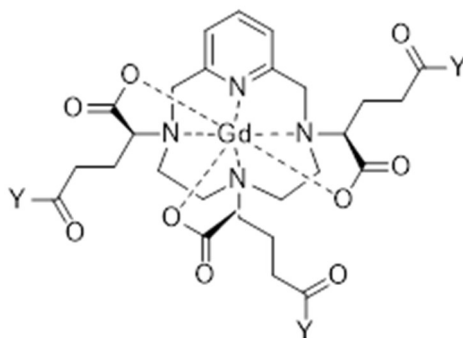


(VII)

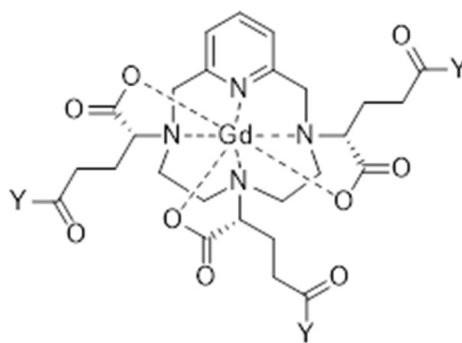
in which Y represents a chlorine atom, a group $-OR_1$ or $-O-C(O)-R_2$; preferably, Y represents a group $-OR_1$ or $-O-C(O)-R_2$, with R_1 and R_2 corresponding, independently of each other, to a (C_1-C_6) alkyl group, and

c2) aminolysis of the activated complex of formula (VII) with 3-amino-1,2-propanediol.

As will be clearly apparent to a person skilled in the art, the reaction for formation of the activated complex of formula (VII) does not modify the absolute configuration of the three asymmetric carbon atoms located in the α position on the side chains, relative to the nitrogen atoms of the macrocycle onto which said side chains are grafted. Consequently, step c1) makes it possible to obtain the activated complex of formula (VII) with a diastereoisomeric excess comprising a mixture of the isomers VII-RRR and VII-SSS, of formulae (VII-RRR) and (VII-SSS) represented below, that is identical to the diastereoisomeric excess comprising a mixture of the isomers I-RRR and I-SSS with which is obtained the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) obtained on conclusion of step b), which is at least 80%.



(VII-SSS),



(VII-RRR).

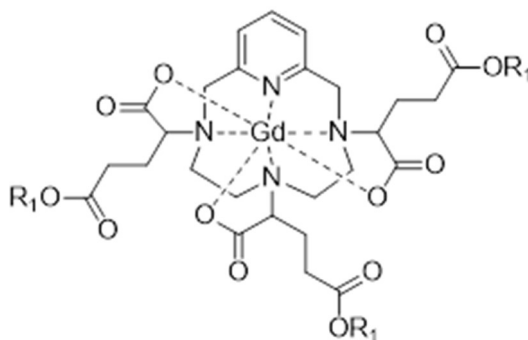
In the case where Y represents a chlorine atom, step c1) is typically performed by reaction between the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) obtained in step b) and thionyl chloride (SOCl₂).

In the case where Y represents an -O-C(O)-CH₃ group, step c1) is typically performed by reaction between the diastereoisomerically enriched hexaacid gadolinium complex of formula (I) obtained in step b) and acetyl chloride.

In an advantageous embodiment, step c) comprises the activation of the abovementioned carboxylic acid (-COOH) functions in the form of ester functions.

According to this embodiment, step c) may more particularly comprise the following successive steps:

c1) formation of a triester of formula (VIII),



(VIII)

in which R₁ represents a (C₁-C₆)alkyl group, and

c2) aminolysis of the triester of formula (VIII) with 3-amino-1,2-propanediol.

Step c1) is typically performed in the alcohol of formula R_1OH , which acts both as solvent and as reagent, in the presence of an acid such as hydrochloric acid.

Step c2) is also typically performed in the alcohol of formula R_1OH , in the presence of an acid such as hydrochloric acid.

- 5 In a first stage, the hexaacid gadolinium complex of formula (I) and the alcohol R_1OH are placed in the reactor. The reaction medium is then cooled to a temperature below $10^{\circ}C$, notably below $5^{\circ}C$, typically to $0^{\circ}C$, and an acidic solution of the alcohol R_1OH , typically of hydrochloric acid in R_1OH , is then gradually added. The reaction medium is kept stirring at room temperature (i.e. at a temperature between 20 and $25^{\circ}C$) for a time typically greater than 5 hours, preferably between 10 hours and 20 hours. The reaction medium is cooled to a temperature below $10^{\circ}C$, notably between $0^{\circ}C$ and $5^{\circ}C$, prior to step c2).

Thus, steps c1) and c2) may be readily performed according to a one-pot embodiment. Advantageously, the triester of formula (VII) is not isolated between steps c1) and c2).

- 15 However, in order to promote the aminolysis reaction, in step c2), the alcohol of formula R_1OH is preferably removed by vacuum distillation.

For the purposes of the present invention, the term "vacuum distillation" means the distillation of a mixture performed at a pressure of between 10 and 500 mbar, notably between 10 and 350 mbar, preferably between 10 and 150 mbar, in particular between 50 and 100 mbar.

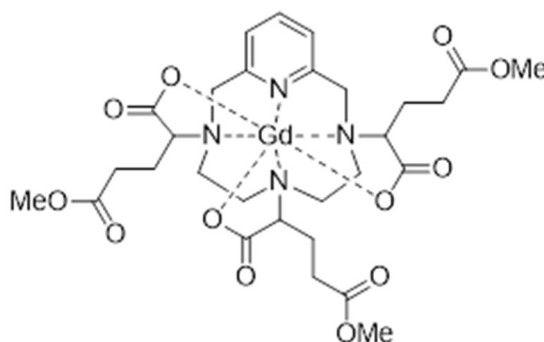
- 20 Similarly, in order to promote the aminolysis reaction, in step c2), 3-amino-1,2-propanediol is introduced in large excess. Typically, the material amount of 3-amino-1,2-propanediol introduced is greater than 4 eq., notably greater than 7 eq., advantageously greater than 10 eq., relative to the material amount of diastereoisomerically enriched hexaacid gadolinium complex of formula (I) initially introduced in step c), which itself corresponds to 1 equivalent.

- Surprisingly, despite the acidic conditions typically employed in steps c1) and c2), which should increase the kinetic instability of the gadolinium complexes, no decomplexation or isomerization of the triester of formula (VIII) is observed. The desired triamide is obtained with a very good degree of conversion and the absolute configuration of the three asymmetric carbon atoms located in the α position on the side chains, relative to the nitrogen atoms of the macrocycle, is conserved.

Moreover, it should be noted that, in general, amidation reactions by direct reaction between an ester and an amine are very sparingly described in the literature (see on this subject K.C. Nadimpally *et al.*, *Tetrahedron Letters*, 2011, 52, 2579-2582).

In a preferred embodiment, step c) comprises the following successive steps:

- 5 **c1)** formation of a methyl triester of formula (IV),



(IV)

notably by reaction in methanol in the presence of an acid such as hydrochloric acid, and

- 10 **c2)** aminolysis of the methyl triester of formula (IV) with 3-amino-1,2-propanediol, notably in methanol in the presence of an acid such as hydrochloric acid.

Advantageously, the methyl triester of formula (IV) is not isolated between steps c1) and c2).

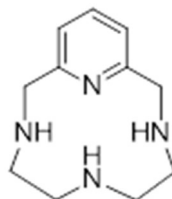
- 15 In a preferred embodiment, in step c2), the methanol is removed by vacuum distillation, until a temperature typically greater than 55°C, notably between 60°C and 65°C is reached, and the reaction medium is maintained at this temperature under vacuum for a time typically greater than 5 hours, notably between 10 hours and 20 hours, before being cooled to room temperature and diluted with water.

- 20 The present invention encompasses all the combinations of the particular, advantageous or preferred embodiments described above in connection with each step of the process.

▪ Preparation of the hexaacid of formula (III)

The hexaacid of formula (III), which participates in step a) of the process for preparing the complex of formula (II) according to the invention, may be prepared according to any method already known and notably according to the methods described in EP 1 931 673.

However, according to a preferred embodiment, the hexaacid of formula (III) is obtained by alkylation of the pyclene of formula (V):



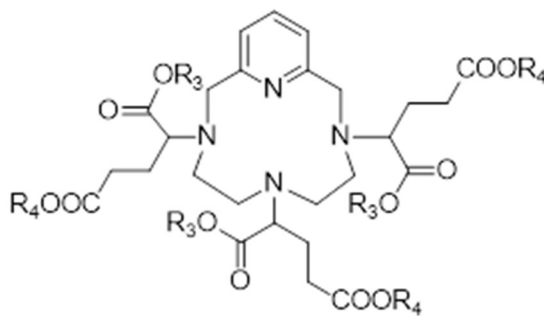
(V)

5 with a compound of formula $R_3OOC-CHG_p-(CH_2)_2-COOR_4$ (IX),

in which:

- R_3 and R_4 represent, independently of each other, a (C_3-C_6) alkyl group, notably a (C_4-C_6) alkyl group such as a butyl, isobutyl, *sec*-butyl, *tert*-butyl, pentyl or hexyl group, and
- 10 - G_p represents a leaving group such as a tosylate or triflate group, or a halogen atom, preferably a bromine atom,

to obtain the hexaester of formula (X)

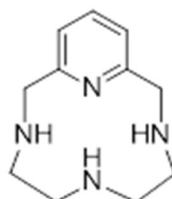


(X)

15 followed by a hydrolysis step, leading to said hexaacid of formula (III).

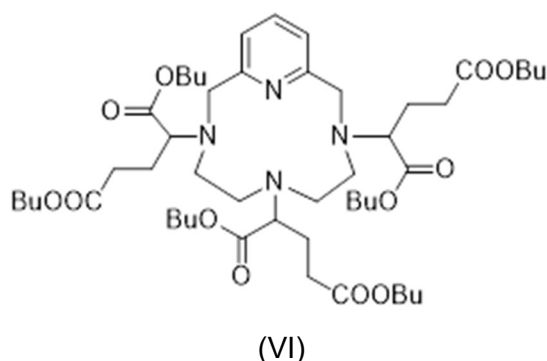
In a preferred embodiment, R_3 and R_4 are identical.

According to an advantageous embodiment, the hexaacid of formula (III) is obtained by alkylation of the pyclene of formula (V):



(V)

with dibutyl 2-bromoglutarate, to obtain the butyl hexaester of formula (VI):



followed by a hydrolysis step, leading to said hexaacid of formula (III).

- 5 The dibutyl 2-bromoglutarate used is in racemic or enantiomerically pure form, preferably in racemic form.

The use of dibutyl 2-bromoglutarate is particularly advantageous, in comparison with the use of ethyl 2-bromoglutarate described in EP 1 931 673. Indeed, commercial diethyl 2-bromoglutarate is a relatively unstable compound, which degrades over time and under the effect of the temperature. More precisely, this ester has a tendency to become hydrolysed or to cyclize and thus to lose its bromine atom. Attempts to purify commercial diethyl 2-bromoglutarate, or to develop new synthetic routes for obtaining it with improved purity, and thus to prevent its degradation, were unsuccessful.

10

The alkylation reaction is typically performed in a polar solvent, preferably in water, in particular in deionized water, advantageously in the presence of a base such as potassium or sodium carbonate.

15

The use of water is preferred notably to that of acetonitrile, described in EP 1 931 673, for obvious reasons.

The reaction is advantageously performed at a temperature of between 40°C and 80°C, typically between 50°C and 70°C and notably between 55°C and 60°C, for a time of between 5 hours and 20 hours, in particular between 8 hours and 15 hours.

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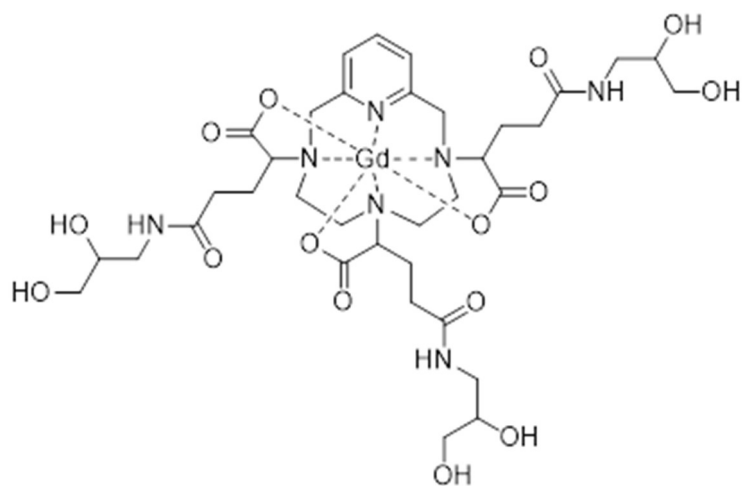
The hydrolysis step is advantageously performed in the presence of an acid or a base, advantageously a base such as sodium hydroxide. The hydrolysis solvent may be water, an alcohol such as ethanol, or a water/alcohol mixture. This step is advantageously performed at a temperature of between 40°C and 80°C, typically between 40°C and 70°C

25

and notably between 50°C and 60°C, typically for a time of between 10 hours and 30 hours, in particular between 15 hours and 25 hours.

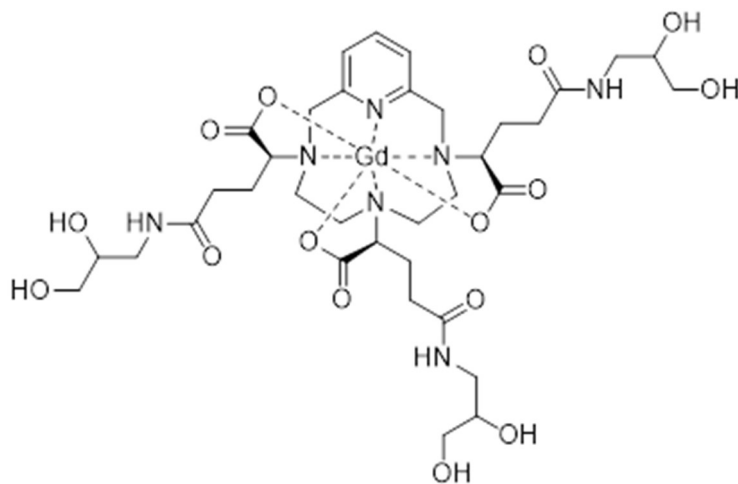
Process for purifying the complex of formula (II)

The present invention furthermore relates to a process for purifying the complex of formula (II) below:

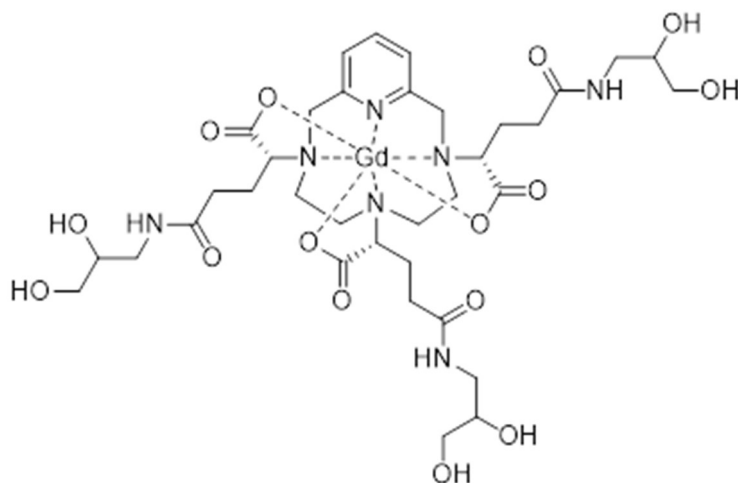


(II)

with at least 80% of a diastereoisomeric excess comprising a mixture of isomers II-RRR and II-SSS of formulae:



(II-SSS)



(II-RRR)

comprising:

- 1) the combination of the following two steps:
 - 1b) passage through ion-exchange resin(s), and
 - 1c) ultrafiltration of said complex, and
- 2) isolation of the purified complex thus obtained in solid form.

Advantageously, said complex of formula (II) having at least 80%, preferentially at least 85%, notably at least 90%, in particular at least 95%, more particularly at least 97%, preferably at least 98% and advantageously at least 99% of a diastereoisomeric excess comprising a mixture of isomers II-RRR and II-SSS was obtained previously according to the preparation process described previously.

In a preferred embodiment, the diastereoisomerically enriched complex on which the purification process is performed has at least 85%, notably at least 90%, in particular at least 92%, preferably at least 94%, advantageously at least 97%, more advantageously at least 99% of the diastereoisomeric excess comprising the mixture of isomers II-RRR and II-SSS.

Preferably, said diastereoisomeric excess is constituted of at least 70%, notably of at least 80%, advantageously of at least 90%, preferably of at least 95% of the mixture of isomers II-RRR and II-SSS.

Advantageously, said diastereoisomeric excess consists of the mixture of isomers II-RRR and II-SSS.

The term "mixture of isomers II-RRR and II-SSS" also covers, by extension, the case where only one of the isomers, whether it be II-RRR or II-SSS, is present. However, the term "mixture of isomers II-RRR and II-SSS" preferentially denotes all the cases in which each of the isomers II-RRR and II-SSS is present in a variable but non-zero amount.

- 5 In a preferred embodiment, the isomers II-RRR and II-SSS are present in said mixture in a ratio of between 65/35 and 35/65, notably between 60/40 and 40/60, in particular between 55/45 and 45/55. Advantageously, the isomers II-RRR and II-SSS are present in the mixture in a 50/50 ratio.

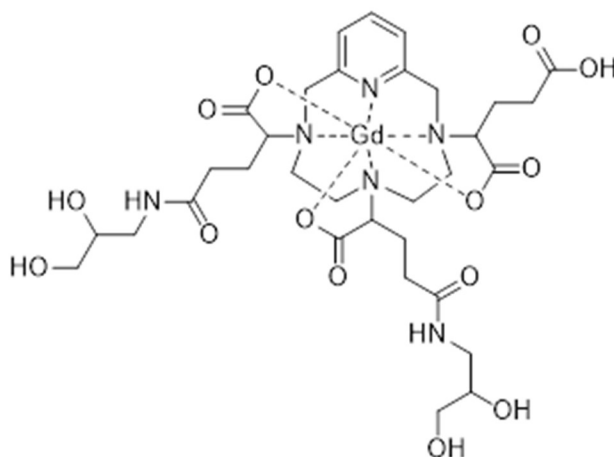
▪ Combination of steps 1b) and 1c)

- 10 Steps 1b) and 1c) are directed towards purifying the complex of formula (II) by removing the impurities that may be present due to its production process.

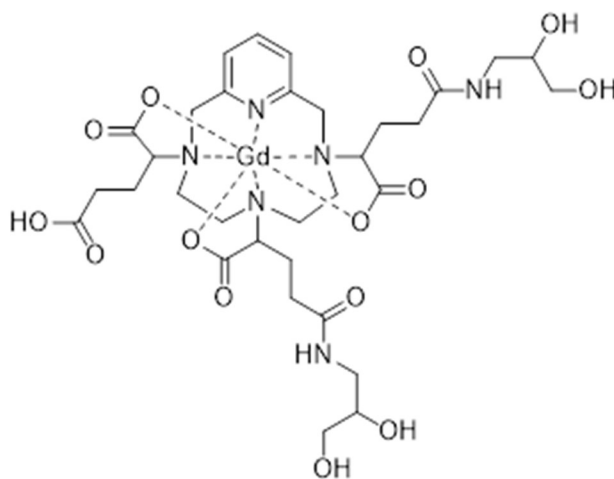
Said impurities may notably comprise 3-amino-1,2-propanediol and/or a dicoupled impurity.

- Indeed, 3-amino-1,2-propanediol may be present in the final product obtained during the implementation of a process for preparing the complex of formula (II), typically when the
- 15 complex of formula (II) is obtained by amidation starting with the complex of formula (I) and 3-amino-1,2-propanediol. This is notably the case for the process for preparing the complex of formula (II) according to the invention. As detailed previously, the amidation reaction may comprise the activation of the three carboxylic acid functions borne by the carbon atoms located in the γ position on the side chains of the complex of formula (I), relative to the
- 20 nitrogen atoms of the macrocycle on which said side chains are grafted, followed by aminolysis of the activated carboxylic acid functions by reaction with 3-amino-1,2-propanediol. The 3-amino-1,2-propanediol is then advantageously used in excess, so as to ensure good conversion into amide functions of the three activated carboxylic acid functions.

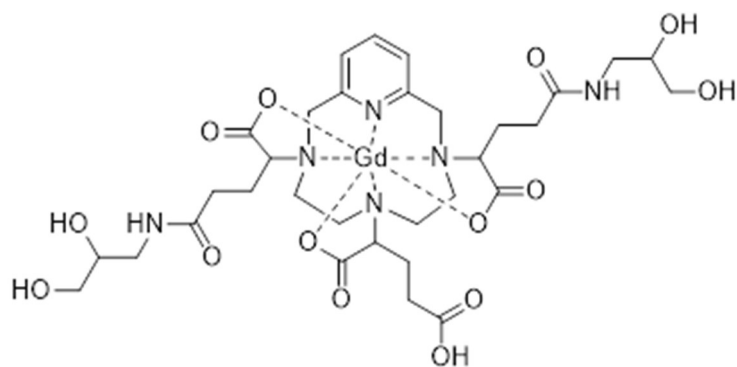
- 25 The term "dicoupled impurity" is intended to denote a complex of formula (II-dc-a), (II-dc-b), (II-dc-c) represented below, or a mixture thereof:



(II-dc-a)



(II-dc-b)



(II-dc-c)

The dicoupled impurity may notably result from the hydrolysis reaction of an amide function of the complex of formula (II). It may also result from incomplete activation of the carboxylic acid functions of the complex of formula (I) (activation of two out of the three functions) or from incomplete aminolysis of the activated carboxylic acid functions (aminolysis of two out

of the three functions), when the process for preparing the complex of formula (II) involves such steps. This is notably the case for the process for preparing the complex of formula (II) according to the invention.

- Step **1b)** corresponds to the passage of the diastereoisomerically enriched complex of formula (II) as described previously through ion-exchange resin(s).

For the purposes of the present invention, the term "ion-exchange resin" means a solid material which is generally in the form of beads composed of a polymer matrix onto which are grafted positively charged functional groups (anionic resin) or negatively charged functional groups (cationic resin), which will make it possible, respectively, to trap anions or cations by adsorption. The adsorption of the anions or cations onto the resin proceeds via ion exchange between the counterions of the functional groups initially present so as to ensure the electrical neutrality of the resin, and the anions or cations intended to be trapped.

Step 1b) involves placing an aqueous solution of the diastereoisomerically enriched complex of formula (II) in contact with a strong anionic resin. The water used is preferably a purified water.

Said strong anionic resin typically includes, as exchanging functional groups, ammonium groups $(N(RR'R''))^+$, in which R, R' and R'' are identical or different (C_1 - C_6)alkyl groups). Mention may notably be made of the resin Amberlite® FPA900 sold by Dow Chemical, advantageously in HO^- form.

Passage through the strong anionic resin makes it possible to at least partly remove the decoupled impurities.

Step 1b) may also involve placing an aqueous solution of the diastereoisomerically enriched complex of formula (II) in contact with a weak cationic resin. The water used is preferably a purified water.

Said weak cationic resin typically includes, as exchanging functional groups, carboxylate groups (CO_2^-). Mention may notably be made of the resin IMAC® HP336 sold by Dow Chemical, advantageously in H^+ form.

Passage through the weak cationic resin makes it possible to at least partly remove the 3-amino-1,2-propanediol, and the possible Gd^{3+} residues.

It should be noted that step 1b) of passage through ion-exchange resin(s) is made possible by the improved stability of the diastereoisomerically enriched complex of formula (II) according to the invention, the integrity of which is consequently preserved during this step.

- Step **1c)** corresponds to ultrafiltration of the diastereoisomerically enriched complex of formula (II) as described previously.

In the present invention, the term "ultrafiltration" means a method of filtration through a mesoporous semi-permeable membrane, the pores of which generally have a diameter of between 1 and 100 nm, in particular between 2 and 50 nm, notably between 10 and 50 nm (mesopores), under the effect of forces such as pressure gradients, typically between 1 and 10 bar, and optionally concentration gradients. It is thus a process of membrane separation via which particles in solution or in suspension whose size is greater than that of the pores are retained by the membrane and separated from the liquid mixture which contained them.

In the context of the purification process according to the invention, ultrafiltration is particularly advantageous for removing endotoxins.

Advantageously, the ultrafiltration membrane used in step 1c) has a cut-off threshold of less than 100 kD, notably less than 50 kD, in particular less than 25 kD, typically a cut-off threshold of 10 kD.

Preferably, in step 1c), the transmembrane pressure is between one and 5 bar, in particular between 2.25 and 3.25 bar.

- In one particular embodiment, steps 1b) and 1c) are also combined with a nanofiltration step **1a)**.

In the present invention, the term "nanofiltration" means a method of filtration through a porous semi-permeable membrane, the pores of which generally have a diameter of between 0.1 and 100 nm, in particular between 0.1 and 20 nm, notably between 1 and 10 nm, under the effect of forces such as pressure gradients, typically between 1 and 50 bar, and optionally concentration gradients. It is thus a process of membrane separation via which particles in solution or in suspension whose size is greater than that of the pores are retained by the membrane and separated from the liquid mixture which contained them.

The nanofiltration step 1a) makes it possible to remove the greater part of the excess 3-amino-1,2-propanediol (optionally in salt form, in particular hydrochloride, or in the form of derivatives, notably the acetamide derivative) and the mineral salts.

5 In this particular embodiment, the nanofiltration step may be performed directly on the crude diastereoisomerically enriched complex of formula (II) as obtained according to the preparation process described previously. It is notably not necessary to precipitate the diastereoisomerically enriched complex of formula (II) prepared previously by adding solvent.

10 Advantageously, the nanofiltration membrane used in step 1a) has a cut-off threshold of less than 1 kD, notably less than 500 daltons, in particular less than 300 daltons, typically a cut-off threshold of 200 daltons.

Preferably, in step 1a), the transmembrane pressure is between 10 and 40 bar, in particular between 2 and 30 bar.

15 In particular, the temperature of the solution of the complex of formula (II) subjected to ultrafiltration in step 1a) is between 20 and 40°C, notably between 25 and 35°C.

In one alternative of this particular embodiment, step 1b) does not involve placing an aqueous solution of the diastereoisomerically enriched complex of formula (II) in contact with a weak cationic resin.

20 In one particular embodiment, the steps 1a), when it is present, 1b and 1c are performed in this order. This advantageous embodiment notably makes it possible to minimize the amounts of resins used and thus the industrial manufacturing cost.

▪ Step 2)

25 Step 2) is directed towards isolating in solid form the purified complex of formula (II) obtained on conclusion of the combination of steps 1b) and 1c), and optionally also combined with step 1a).

This step of isolation in solid form may be performed according to any method that is well known to those skilled in the art, notably by atomization, by precipitation, by lyophilization or by centrifugation, advantageously by atomization.

In a preferred embodiment, step 2) comprises atomization.

Specifically, isolation in solid form of the purified complex of formula (II) by atomization makes it possible notably to dispense with the use of precipitation solvents.

The air inlet temperature in the atomizer is then typically between 150°C and 180°C, notably between 160°C and 175°C, advantageously between 165°C and 170°C. The outlet temperature is itself typically between 90°C and 120°C, preferably between 105°C and 110°C.

Advantageously, the degree of purity of the purified complex of formula (II) diastereoisomerically enriched in the mixture of isomers II-RRR and II-SSS isolated on conclusion of step 2) is greater than 95%, notably greater than 97%, preferentially greater than 97.5%, more preferentially greater than 98%, advantageously greater than 99%, said degree of purity being expressed as a mass percentage of the complex of formula (II) relative to the total mass obtained on conclusion of step 2).

The present invention also relates to the diastereoisomerically enriched and purified complex of formula (II) which may be obtained according to the purification process of the invention.

Preferably, the complex of formula (II) included in the composition according to the invention described previously is the diastereoisomerically enriched and purified complex of formula (II) which may be obtained according to the purification process of the invention.

EXAMPLES

The examples given below are presented as non-limiting illustrations of the invention.

Separation of the groups of isomers iso1, iso2, iso3 and iso4 of the complex of formula (II) by UHPLC

A UHPLC machine constituted of a pumping system, an injector, a chromatography column, a UV detector and a data station is used. The chromatography column used is a UHPLC 150 × 2.1 mm - 1.6 µm column (Waters Cortecs® UPLC T3 column).

Mobile phase:

Route A: 100% acetonitrile and Route B: aqueous solution of H₂SO₄ (96%) at 0.0005%

v/v

- Preparation of the test solutions:

Solution of the complex of formula (II) at 2 mg/mL in purified water

- Analytical conditions:

Column temperature	40°C
Sample temperature	Room temperature (20-25°C)
Flow rate	0.3 ml/min
Injection volume	1 µl
UV detection	200 nm
Analysis time	20 min

- Gradient:

Time	% Acn	% H ₂ SO ₄ 0.0005%
0	1	99
3	5	95
12	10	90
15	25	75
16	1	99
20	1	99

- 5 Four main peaks are obtained. Peak 4 of the UHPLC plot, namely iso4, corresponds to a retention time of 6.3 minutes.

Preparation of the butyl hexaester of formula (VI)

- 184 kg (570 mol) of dibutyl 2-bromoglutarate and 89 kg (644 mol) of potassium carbonate are mixed in a reactor and heated to 55-60°C. An aqueous solution of 29.4 kg (143 mol) of pyclyene in 24 kg of water is added to the preceding preparation. The reaction mixture is maintained at 55-60°C and then refluxed for about 10 hours. After reaction, the medium is cooled, diluted with 155 kg of toluene and then washed with 300 litres of water. The butyl hexaester is extracted into the aqueous phase with 175 kg (1340 mol) of phosphoric acid (75%). It is then washed three times with 150 kg of toluene. The butyl hexaester is re-
15 extracted into a toluene phase by dilution with 145 kg of toluene and 165 kg of water, followed by basification with 30% sodium hydroxide (m/m) to reach a pH of 5-5.5. The lower aqueous phase is removed. The butyl hexaester is obtained by concentrating to dryness under vacuum at 60°C, in a yield of about 85%.

Preparation of the hexaacid of formula (III)

113 kg (121 mol) of butyl hexaester are placed in a reactor along with 8 kg of ethanol. The medium is brought to $55 \pm 5^\circ\text{C}$ and 161 kg (1207.5 mol) of 30% sodium hydroxide (m/m) are then added over 3 hours. The reaction mixture is maintained at this temperature for about 20 hours. The butanol is then removed by decantation of the reaction medium. The
 5 hexaacid of formula (III) obtained in sodium salt form is diluted with water to obtain an aqueous solution of about 10% (m/m). This solution is treated on an acidic cationic resin. The hexaacid of formula (III) in aqueous solution is obtained in a yield of about 90% and a purity of 95%.

Preparation of the hexaacid gadolinium complex of formula (I)

10 ▪ ***Experimental protocol***

• Complexation and isomerization

- *Without acetic acid*

418 kg (117 kg of pure hexaacid of formula (III)/196 mol) of an aqueous solution of hexaacid of formula (III) at 28% by weight are placed in a reactor. The pH of the solution is adjusted
 15 to 2.7 by adding hydrochloric acid, and 37 kg (103.2 mol) of gadolinium oxide are then added. The reaction medium is heated at $100\text{--}102^\circ\text{C}$ for 48 hours to achieve the expected isomeric distribution of the hexaacid of formula (III).

- *With acetic acid*

Gadolinium oxide (0.525 molar eq.) is suspended in a solution of hexaacid of formula (III)
 20 at 28.1% by mass.

99-100% acetic acid (50% by mass/pure hexaacid of formula (III)) is poured into the medium at room temperature.

The medium is heated to reflux followed by distillation up to 113°C by mass by refilling the medium with acetic acid gradually as the water is removed. Once the temperature of 113°C
 25 is reached, a sufficient amount of acetic acid to arrive at the starting volume is added.

The medium is maintained at 113°C overnight.

• Crystallization, recrystallization

- *Crystallization*

The hexaacid gadolinium complex of formula (I) in solution is cooled to 40°C, the primer is added and the agents are left in contact for at least 2 hours. The product is then isolated by filtration at 40°C and washed with osmosed water.

- *Recrystallization*

- 5 180 kg of the hexaacid gadolinium complex of formula (I) obtained previously (solids content of about 72%) are suspended in 390 kg of water. The medium is heated to 100°C to dissolve the product, and then cooled to 80°C to be primed by adding a small amount of primer. After cooling to room temperature, the hexaacid gadolinium complex of formula (I) is isolated by filtration and drying.

10 • Selective decomplexation

The dry product is placed in the reactor with osmosed water at 20°C. The mass of water added is equal to twice the theoretical mass of hexaacid gadolinium complex of formula (I). 30.5% sodium hydroxide (m/m) (6.5 eq.) is poured into the medium at 20°C. At the end of the addition of NaOH, the medium is left in contact at 50°C for 16 hours. The medium is
15 cooled to 25°C and the product is filtered off on a bed of Clarcel.

▪ ***Content of the mixture of diastereoisomers I-RRR and I-SSS***

The ratio in which the various isomers of the complex of formula (I) are present in the mixture of diastereoisomers depends on the conditions under which the complexation and isomerization steps are performed, as is seen in Table 3 below.

<i>pH</i>	<i>Temperature</i>	<i>Content of hexaacid of formula (III)</i>	<i>Time</i>	<i>Diastereoisomeric excess in the mixture I-RRR and I-SSS</i>
5.7	80°C	40%	3 hours	19%
3.5	90°C	50%	10 hours	49%
3.0	101°C	40%	10 hours	68%
2.7	101°C	28%	48 hours	98.04%

20 Table 3: content of the mixture I-RRR and I-SSS as a function of the complexation / isomerization conditions

The additional steps of recrystallization and selective decomplexation make it possible to increase the diastereoisomeric excess of the mixture I-RRR and I-SSS (see Table 4).

	<i>After the first crystallization</i>	<i>After recrystallization</i>	<i>After selective decomplexation</i>
<i>Diastereoisomeric excess in the mixture I-RRR and I-SSS</i>	98.04%	99.12%	99.75%

Table 4: content of the mixture I-RRR and I-SSS after crystallization/recrystallization/selective decomplexation

5 **Preparation of the complex of formula (II)**

90 kg (119 mol) of the hexaacid complex of formula (I) and 650 kg of methanol are placed in a reactor. The mixture is cooled to about 0°C and 111 kg (252 mol) of a methanolic solution of hydrochloric acid (8.25% of HCl in methanol) are then poured in while maintaining the temperature at 0°C. The reaction medium is brought to room temperature and stirring is then continued for 16 hours. After cooling to 0-5°C, 120 kg (1319 mol) of 3-amino-1,2-propanediol are added. The reaction medium is then heated while distilling off the methanol under vacuum until a temperature of 60-65°C is reached. The concentrate is maintained for 16 hours at this temperature under vacuum. At the end of contact, the medium is diluted with 607 kg of water while cooling to room temperature. The solution of the crude complex of formula (II) is neutralized with 20% hydrochloric acid (m/m). 978.6 kg of solution are thus obtained, with a concentration of 10.3%, representing 101 kg of material. The yield obtained is 86.5%, the purity of the complex of formula (II) is 92.3% (HPLC s/s). The amount of decoupled impurities is 6.4% (HPLC s/s).

Purification of the complex of formula (II)

20 • **Nanofiltration**

The nanofiltration membrane used has a cut-off threshold of 200 daltons (Koch Membran System SR3D). This treatment is performed in the following manner:

The solution of crude complex of formula (II) is heated to 30°C. The nanofilter is filled with said solution. The pump is switched on first at a low rate to purge the system, then the rate of the nanofilter pump is gradually increased to the desired recirculation rate (1.0 m³/h for a membrane of 2.5 × 40 inches). The system is then placed in total recirculation at 30°C for at least 2 hours to establish a polarization layer. The medium is then passed to diafiltration at 30°C under 2.5 bar while keeping the volume constant by adding pure water

until a conductivity of the retentate of less than 1000 μS is obtained. At the end of diafiltration, the medium is concentrated to obtain a concentration of about 40% (m/m).

- Treatment on resins

5 The solution of complex of formula (II) obtained from the nanofiltration is diluted with purified water with stirring to obtain a 15% solution (m/m). This solution is eluted in series on 50 litres of strong anionic resins (FPA900) in OH^- form and then on 50 litres of weak cationic resins (HP336) in H^+ form at a mean elution flow rate of 2V/V/H (2 volumes of solution per volume of resin per hour). The resins are then rinsed with about 450 litres of purified water until a refractive index of less than 1.3335 is obtained.

10 The solution of complex of formula (II) is then concentrated by heating to 50-60°C under a vacuum of 20 mbar to reach a concentration of 35% (m/m).

- Ultrafiltration

The ultrafiltration membrane is a UF 10KD Koch Spiral membrane.

15 The ultrafilter is fed with the preceding solution of complex of formula (II) at 35% heated to 40°C. The ultrafiltration is applied at a flow rate of 3 m^3/h with a transmembrane pressure of 2.5-3 bar. The system is rinsed several times with 13 litres of apyrogenic purified water until a final dilution of the complex of formula (II) of 25% (m/m) is reached.

- Atomization

20 The complex of formula (II) is obtained in powder form by atomization of the preceding solution of complex of formula (II) concentrated to 25%.

The atomization is performed in the following manner:

The atomizer is equilibrated with apyrogenic pure water by setting the inlet temperature to 165°C-170°C and adapting the feed rate such that the outlet temperature is between 105 and 110°C.

25 The concentrated solution of complex of formula (II) is then added and the flow rate is adjusted so as to conserve the above parameters.

These operating conditions are maintained throughout the atomization, while ensuring good behaviour of the powder in the atomization chamber and at the atomizer outlet. It should notably be ensured that there is no adhesion of the product.

At the end of feeding the atomizer with the solution, the container of this complex of formula (II) and the atomizer are rinsed with apyrogenic pure water until maximum recovery of the powder is obtained.

A 99.6% pure complex of formula (II) is obtained.

This degree of purity was determined by reverse-phase liquid chromatography.

Composition according to the invention and results of studies thereon

10 • Example of a manufacturing process in accordance with the invention

The process for manufacturing a composition according to the invention is performed according to the following steps:

a) 485.1 g (i.e. 0.5 M) of complex of formula (II) are dissolved in water (qs 1 litre), heating the tank to a temperature of between 39 and 48°C and stirring the solution vigorously until this complex has fully dissolved in the water. The solution is then cooled to about 30°C.

b) 0.404 g (i.e. 0.2 mol/mol% relative to the proportion of complex added in step a)) of DOTA (Simafex, France) is added with stirring to the solution obtained in step a) via a solution of DOTA at 10% m/v.

c) Trometamol (Tris) is added to the solution obtained in step b) with stirring. The pH is then adjusted to a value of between 7.2 and 7.7 by addition of hydrochloric acid solution with stirring.

d) The target concentration (0.5 mol/L) is obtained by adding water for injection in two steps until a density value of between 1.198 and 1.219 g/mL is obtained.

The liquid composition is then filtered through a polyethersulfone membrane and placed in its final container, which is finally sterilized at 121°C for 15 minutes.

• Example of a composition in accordance with the invention.

The following formulation is obtained by means of the process described above:

Ingredients	Proportions in the composition
Complex of formula (II)	485.1 g (0.5 M)
DOTA**	0.404 g (1 mM, i.e. 0.2 mol/mol% versus complex)
NaOH or HCl	qs pH 7.2 to 7.7
Trometamol	1.211 g
Free gadolinium*	< 1 ppm m/v
Water for injection (injection-grade)	qs 1 L

* Measurement performed by the colorimetric method with xylenol orange

**expressed on an anhydrous and pure basis

- Formulation tests performed

- 5 Various concentrations of trometamol from 0 to 100 mM were tested. The results of these tests showed that a content of 10 mM (0.12% w/v) was sufficient to ensure the pH stability of the formulation while limiting the formation of degradation impurities.

- Various concentrations of DOTA from 0 to 2.5 mM were tested. The results of these tests showed that a content of 1 mM, which corresponds to 0.04% m/v or 0.2 mol/mol%, makes
10 it possible to ensure the absence of release of free Gd during the process and during the lifetime of the product.

- Stability studies under accelerated conditions of a composition according to the invention

- The formulation of the preceding example is analysed just after its manufacture (T_0) and
15 after storage at 40°C for 6 months after its manufacture ($T+6$ months).

At T_0 :

- Purity evaluated by chromatography*: 99.6%
- Concentration of Gd-DOTA: 0.007% (m/V)
- Concentration of Gd: below 0.0001% (m/V)
- 20 - pH: 7.5

At $T+6$ months:

- Purity evaluated by chromatography*: 97.2%
- Concentration of Gd-DOTA: 0.014% (m/V) - 0.25 mM
- Concentration of Gd: below 0.0001% (m/V)

- pH: 7.5

* reverse-phase liquid chromatography

These results demonstrate that this formulation has good stability over time.

5 • Comparative stability studies

The stability of the compositions below was evaluated over time. The term "non-optimized AP" denotes the active principle, namely the complex of formula (II), obtained according to the process described in EP 1 931 673. The term "optimized AP" denotes the diastereoisomerically enriched and purified complex of formula (II) obtained via the process according to the invention.

	AP (0.5 M)	[DOTA] mol/mol%	Trometamol mM	pH _{adjustment}
C1	Not optimized	0.3	-	5.0
C2	Optimized	0.2	-	7.5
C3	Optimized	0.1	-	7.5
C4	Optimized	0.2	10	7.5
C5	Optimized	0.1	10	7.5
C6	Optimized	0.2	-	5.0
C7	Optimized	0.1	-	5.0

	Free Gd in ppm m/v (xylene ^o)		DOTA-Gd in mol/mol% (LC formate*)	
	T 0	T 6 months 40°C	T 0	T 6 months 40°C
C1	< DL	0.18	0.27	0.3
C2	< DL	< DL	0.02	0.05
C3	< DL	< DL	0.02	0.05
C4	< DL	< DL	0.02	0.05
C5	< DL	< DL	0.02	0.08
C6	< DL	< DL	0.03	0.03
C7	< DL	< DL	0.02	0.07

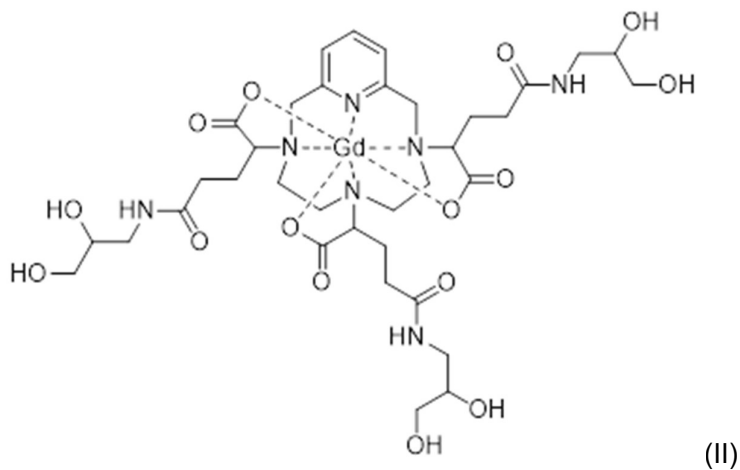
* LC formate: chromatographic method involving fluorimetric detection. The separation is performed on a reverse-phase C18 grafted chromatography column with elution in gradient mode.

The results reported above indicate that formulation of the non-optimized AP with free DOTA is not possible. The reason for this is that the chelation excipient is entirely consumed by the trans-ligation reaction between the complex of formula (II) and DOTA and consequently can no longer play its role of trapping the leached Gd^{3+} .

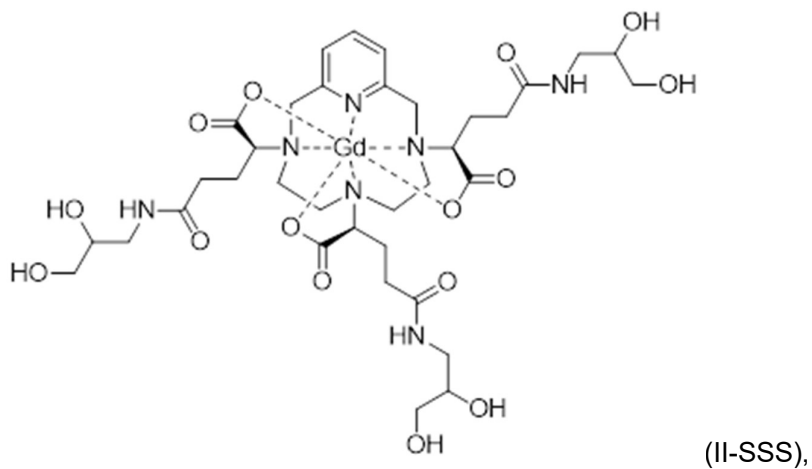
- 5 On the other hand, the diastereoisomerically enriched and purified complex of formula (II) obtained via the process according to the invention may be formulated with free DOTA. Specifically, the absence of free Gd in the composition at 6 months, 40°C, is observed, this being the case irrespective of the pH of the formulation and whether or not buffering species are present. In addition, the consumption of chelation excipient is very low, since it does
- 10 not exceed 0.08 mol/mol%.

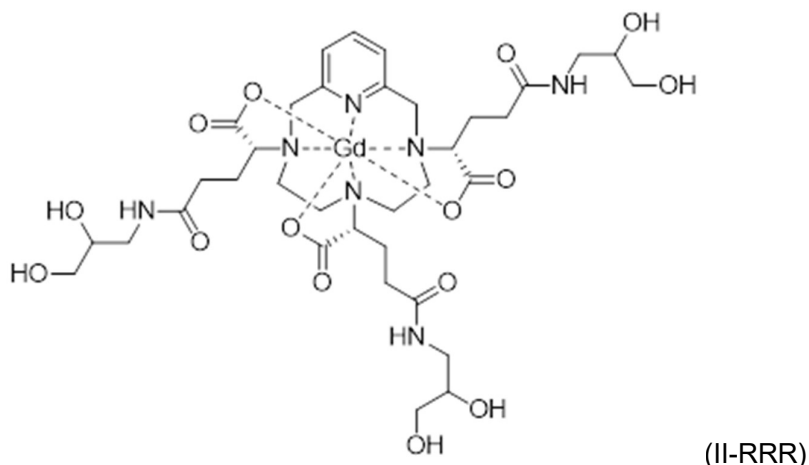
CLAIMS

1. Composition comprising the complex of formula (II) below:



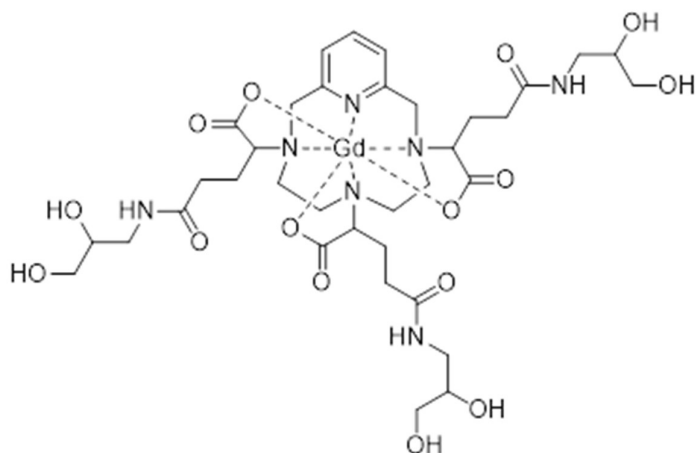
constituted of at least 80% of a diastereoisomeric excess of diastereoisomers II-RRR and II-SSS of formulae:





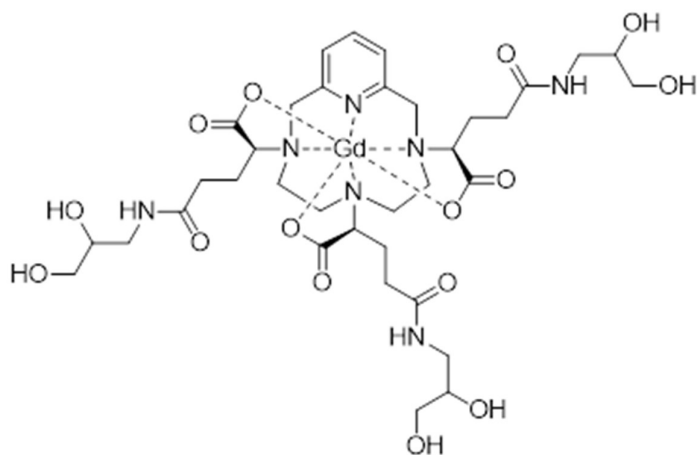
and a free macrocyclic ligand selected from the group consisting of DOTA, NOTA, DO3A, BT-DO3A, HP-DO3A, PCTA and DOTA-GA, wherein the composition has a concentration of free gadolinium of less than 1 ppm (m/v), and wherein the composition comprises between 0.002 and 0.4 mol/mol% of free DOTA relative to the complex of formula (II).

2. Composition according to Claim 1, wherein the free macrocyclic ligand is 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid (DOTA).
3. Composition according to claim 1 or 2, wherein the composition has a concentration of the complex of formula (II) of between 0.01 mol.L⁻¹ and 1.5 mol.L⁻¹, preferably between 0.3 and 0.6 mol.L⁻¹.
4. Composition according to any of claims 1 to 3, wherein the pH of the composition is between 4.5 and 8.5, preferably between 6.5 and 8.
5. Composition according to any of claims 1 to 4, wherein the composition further comprises a buffer selected from the group consisting of lactate, tartrate, malate, maleate, succinate, ascorbate, carbonate, Tris (Tris(hydroxymethyl)aminomethane), HEPES (2-[4-(2-hydroxyethyl)-1-piperazine]ethanesulfonic acid) and MES (2-morpholinoethanesulfonic acid) buffers and mixtures thereof, preferably the buffer is Tris.
6. Process for purifying the complex of formula (II) below:

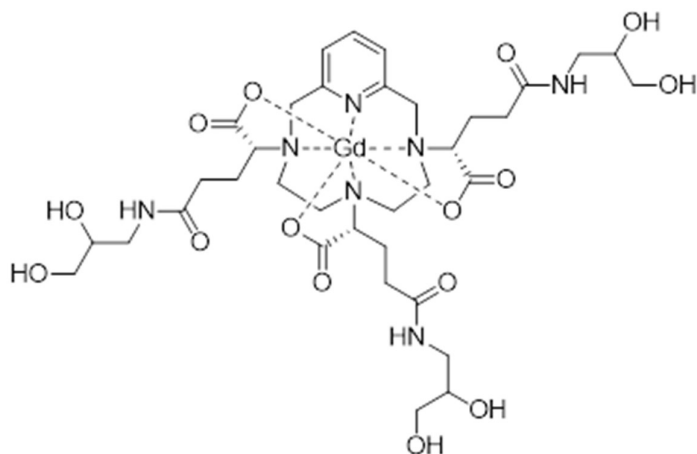


(II)

constituted of at least 80% of a diastereoisomeric excess of diastereoisomers II-RRR and II-SSS of formulae:



(II-SSS),



(II-RRR),

comprising:

1) the combination of the following two steps:

1b) passage through ion-exchange resin(s), and

1c) ultrafiltration of said complex, and

2) isolation of the purified complex thus obtained in solid form.

7. Process according to Claim 6, wherein steps 1b) and 1c) are also combined with a nanofiltration step 1a).

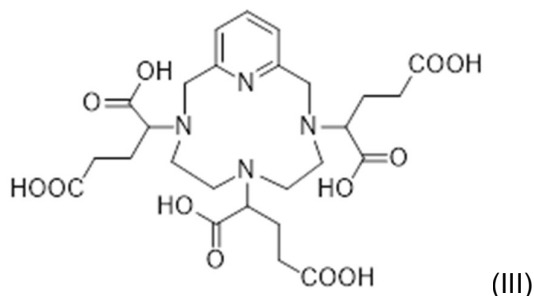
8. Process according to Claim 6 or 7, wherein the steps 1a), when it is present, 1b) and 1c) are performed in this order.

9. Process according to any one of Claims 6 to 8, wherein step 2) comprises atomization.

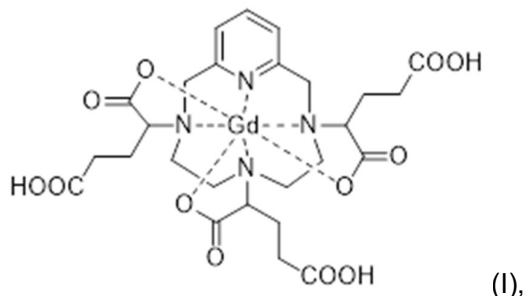
10. Process according to any one of Claims 6 to 9, wherein step 1b) further comprises contacting the aqueous solution of the complex of formula (II) with a cationic resin, and/or with an anionic resin.

11. Process according to any one of Claims 6 to 10, wherein the process further comprises the following successive steps prior to steps 1) and 2):

a) complexation of an hexaacid of formula (III) below:



with gadolinium to obtain a hexaacid gadolinium complex of formula (I) below:



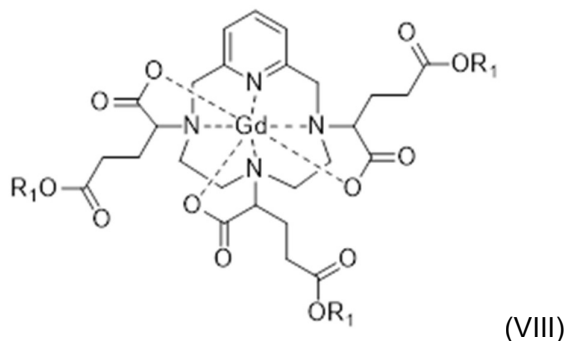
b) isomerization by heating the hexaacid gadolinium complex of formula (I) in an aqueous solution at a pH of between 2 and 4, to obtain a diastereoisomerically enriched complex

constituted of at least 80% of a diastereoisomeric excess comprising a mixture of the isomers I-RRR and I-SSS of said hexaacid gadolinium complex of formula (I), and

c) formation, starting with the diastereoisomerically enriched complex obtained in step b), of the complex of formula (II) as defined in claim 6, by reaction with 3-amino-1,2-propanediol.

12. Process according to Claim 11, wherein:

- on conclusion of step b), the diastereoisomerically enriched complex is isolated by crystallization, purified by recrystallization and further enriched by selective decomplexation of the diastereoisomers of the complex of formula (I) other than the diastereoisomers I-RRR and I-SSS, *i.e.* by selective decomplexation of the diastereoisomers I-RSS, I-SRR, I-RSR, I-SRS, I-RRS and I-SSR, and
- step c) comprises the following successive steps:
 - c1) formation of a triester of formula (VIII),



in which R_1 represents a (C_1-C_6) alkyl group,

notably by reaction in the alcohol of formula R_1OH in the presence of an acid such as hydrochloric acid, and

c2) aminolysis of the triester of formula (VIII) with 3-amino-1,2-propanediol,

notably in the alcohol of formula R_1OH in the presence of an acid such as hydrochloric acid,

the triester of formula (VIII) not being isolated between steps c1) and c2).