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Coordination Chemistry Reviews 226 (2002) 227–234

COORDINATION CHEMISTRY REVIEWS

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Recognition and sensing of chiral biological substrates via lanthanide coordination chemistry

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Received 4 April 2001; accepted 15 October 2001

Contents

Abstract

A series of lanthanide tris(β-diketonates) and porphyrinates was developed as effective receptors which offered chiral recognition and chirality sensing of biological substrates. These lanthanide complexes were electrically neutralized by coordinating ligands but further formed highly coordinated complexes with various substrates. We optimized the combination of coordinating ligand and lanthanide center to realize specific recognition and sensing of chiral amino alcohols and amino acids. Two further approaches were successful: (1) substitution of lanthanide tris(β-diketonates) with chiral ligands provided efficient enantiomer-selective extraction of zwitterionic amino acids; and (2) functionalization of lanthanide porphyrinates with highly structured functions enhanced the sensitivity in CD probing of chiral amino acids. Since the lanthanide complexes have broad structural variations, the molecular recognition phenomena described here offer promising possibilities in developing a new class of chiral recognition and chirality sensing systems incorporating intelligent lanthanide complexes.

Keywords: Lanthanide tris(β-diketonate); Lanthanide porphyrinate; Extraction; CD sensing; Molecular recognition

1. Introduction

Lanthanide tris(β-diketonates) and porphyrinates are representatives of rare earth metal complexes and exhibit interesting chemical, biological and catalytic properties [1]. Although these are electrically neutralized by anionic ligands, one or more additional substrates usually bind to the lanthanide centers, increasing the coordination number to more than 6. Based on the highly coordinated complexation, various lanthanide tris(β-diketonates) and related complexes work as shift reagents in NMR spectroscopy [2], catalysts in organic synthesis [3], and probes in the areas of clinical chemistry and molecular biology [4]. The most striking feature of these lanthanide complexes is that their coordination chemistry is different from that of com-

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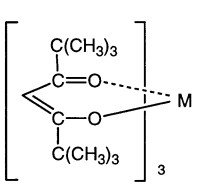
0010-8545/02/$ - see front matter
PII: S0010-8545(01)00450-7

mon transition metal complexes. The lanthanide centers have larger ion-radii and coordination numbers (7–12) [5], and form a variety of ternary complexes [6]. Although their versatile coordination chemistry offered potential applications in the design of intelligent lanthanide complexes [1,7], we recently developed chiral recognition and chirality sensing systems incorporating lanthanide complexes [8]. The enantiomer-selective extraction of zwitterionic amino acids, the chirality sensing of biogenetic amines and unprotected amino acids and the optical purity determination of amino alcohols were successfully realized by structural optimization and sophistication of lanthanide tris(β-diketonates) and porphyrinates.

This review summarizes our original efforts to develop a novel type of lanthanide complex-based receptor for chiral biological substrates [9–12]. It focuses primarily on characteristic lanthanide coordination chemistry and its applications in recognition and sensing of chiral substrates. The lanthanide tris(β-diketonates) and porphyrinates are characterized here as a new series of receptors. The former are known to bind additional substrates in crystal and solution states [6]. As schematically illustrated in Fig. 1, lanthanide tris(2,2,6,6-tetramethyl-3,5-heptanedionates) (**1**) were reported typically to bind two pyridine molecules without loss of three diketonate ligands [6]. Nakanishi and Dillon have applied complex **1** (M = Pr) in the chirality sensing using CD method. It interacted with chiral 1,2-diols in non-polar solvents and the resulting ternary complexes gave split-type Cotton effects at the ligand absorption region [13]. Since the sign of the observed CD signal related to the absolute configuration of the substrate, this CD method was useful in the stereochemistry determination of several natural products [14]. The intraconfigurational f–f transition of the lanthanide center can be applicable in the CD probing of



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Effective Ionic Radius (pm)

Pr^{3+} = 113	Eu^{3+} = 107
Gd^{3+} = 105	Dy^{3+} = 103
Ho^{3+} = 102	Yb^{3+} = 99

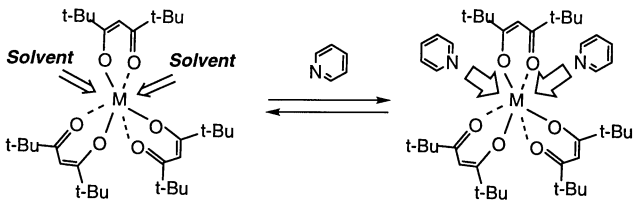


Fig. 1. Effective ionic radius of lanthanide centers and highly coordinated complexation.

chiral substrates [4b]. Brittain [15] and Riehl and coworkers [16] reported that the addition of chiral sugars to the lanthanide tris(2,6-pyridinecarboxylates) offered characteristic circularly polarized luminescence (CPL) behavior. More recently, Parker et al. presented CPL sensing of lactate, citrate and acetate [17]. Chiral lanthanide tris(β-diketonates) were widely employed as chiral shift reagents in ^{1}H- and ^{13}C-NMR spectroscopy [18]. The enantiomers of chiral substrates formed diastereomeric complexes with chiral lanthanide reagents and often exhibited separated signals at different chemical shifts. Lanthanide porphyrinates also have potential as non-destructive probes in medical analysis [19], because they have well-defined structures and intense Soret-bands around 400 nm [20]. Radzki and Giannotti reported that the lanthanide porphyrinates gave significant UV spectral changes upon complexation with achiral amines, phenols and nucleic bases [21]. Such highly coordinated complexes have frequently been involved in various lanthanide complex systems but have rarely been characterized from the standpoints of coordination chemistry and molecular recognition science.

We have demonstrated that a series of lanthanide tris(β-diketonates) such as **2** exhibited characteristic carrier functions for anionic amino acid derivatives [22,23]. They effectively bound organic anions such as *Z*-amino acid anions, while the inorganic anions Cl^- and Br^- were modestly complexed. As expected, the fluorinated ligand promoted subsequent anion coordination with lanthanide centers and enhanced the carrier activities. Furthermore, zwitterionic amino acids were effectively extracted and transported by several lanthanide tris(β-diketonates). These successful applications have stimulated interest in the further evolution of ligands in an attempt to develop new lanthanide complexes with excellent receptor functions. Several structural modifications of lanthanide tris(β-diketonates) **2** and porphyrinates **4** led to a new generation of effective receptors (Fig. 2). Introduction of chiral fluorinated β-diketonate ligands realized chiral recognition via diastereomeric complexation in the binding of amino alcohols and liquid–liquid extraction of zwitterionic amino acids. Substitution by chromophoric porphyrinate ligands and further hybridization with characteristic functional molecules remarkably enhanced the sensing ability for chiral biological substrates. Although we present here only a limited number of examples, the lanthanide complexes have many applications in various fields of chirality science and technology.

2. Chirality sensing by lanthanide tris(β-diketonates)

When the chirality of non-chromophoric substrate is determined using CD spectroscopy, an intense chro-

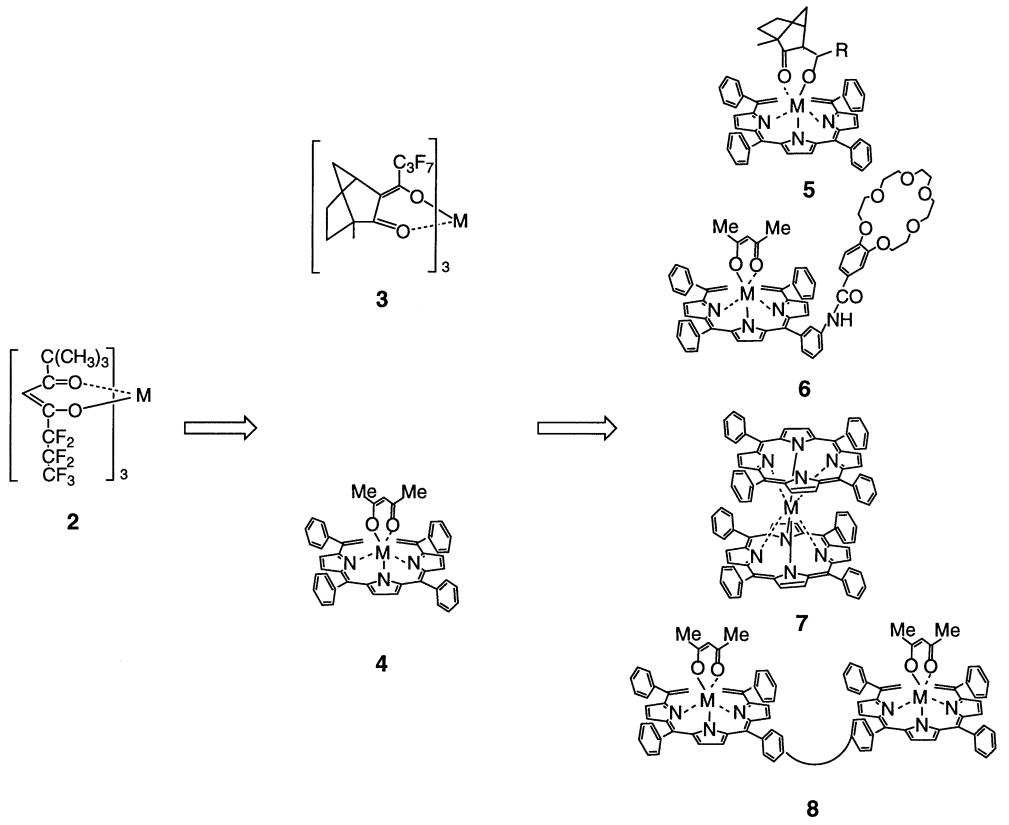
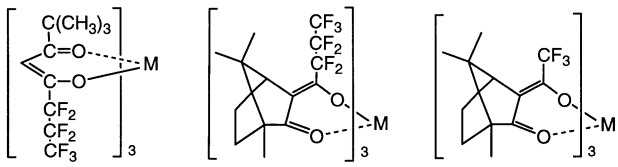


Fig. 2. Receptor evolution based on lanthanide coordination chemistry.

mophore should be attached in a proper fashion by derivatization or complexation method. The derivatization method was frequently applied in the literature, involved covalent bond formation between substrate and chromophore [24]. The complexation method was recently recognized as a promising alternative [8b], because the chromophore bound the substrate via a non-covalent interaction. Resorcinol cyclic tetramers, calixarenes, polymer helices, porphyrins and diboronic acid derivatives were developed as chromophoric probes for this purpose [25]. This complexation method has the great advantage of simplicity in experiments: only several micrograms of substrate is required; neither coupling reaction nor purification is needed; and recovery of substrate is very easy [8,24b].

Among a series of lanthanide tris(β-diketonates) as shown in Fig. 3, complexes **2** having achiral 1,1,1,2,2,3,3-heptafluoro-7,7-dimethyl-4,6-octadionate ligands acted as effective probes for the chirality sensing of amino alcohols. The targeted chiral amino alcohols are useful building blocks in asymmetric organic synthesis as well as biological substrates for ethanol–amine ammonia-lyase [26]. Although substrates and lanthanide tris(β-diketonates) are silent in CD spectra (>250 nm), they form highly coordinated complexes which exhibit induced CD signals around 300 nm. Europium tris(fluorinated β-diketonate) **2** (M = Eu) typically gave steady CD signal upon complexation with (*R*)- or (*S*)-2-amino-1-propanol (Fig. 4). Interestingly, symmetric CD spectra were recorded in the presence of enantiomers of amino alcohol substrate [12]. When chiral monoamine, monoalcohol and diol were employed as targeting substrates, they did not cause any change in the CD spectra. Since **2** (M = Eu) bound these substrates much more weakly than amino alcohols, this functioned as a chemo-selective CD probe of



M^{3+}	
Pr^{3+}	Eu^{3+}
Gd^{3+}	Dy^{3+}
Ho^{3+}	Yb^{3+}

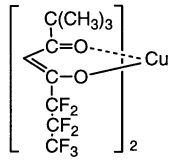


Fig. 3. Lanthanide tris(β-deketonates) and reference probes.

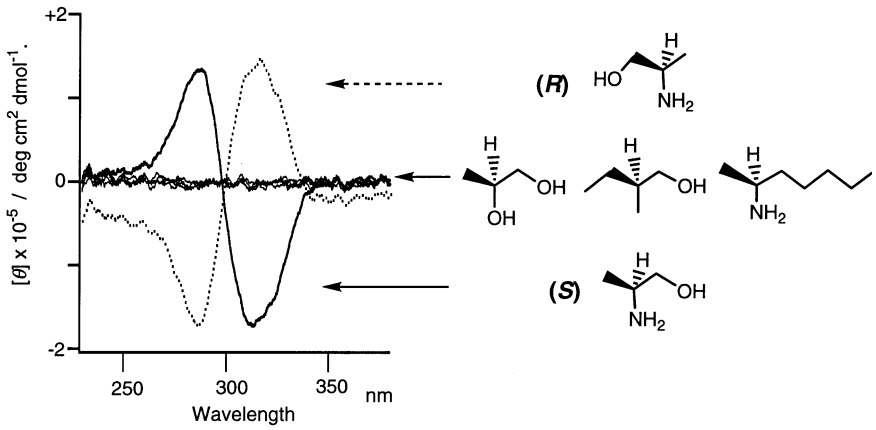


Fig. 4. Induced CD spectra of europium tris(fluorinated β-diketonate) **2** (M = Eu) in the presence of chiral substrates (see Ref. [12]) [**2**] = 3.5×10^{-5} mol l^{-1}; [substrate] = 3.5×10^{-4} mol l^{-1} in CH_3OH–CH_2Cl_2 (1/99).

chiral amino alcohols. The sign of the induced CD signal can be predicted by assuming the bidentate coordination model of chiral amino alcohol (Fig. 5). When (*S*)-2-amino-1-propanol coordinates with the lanthanide center in a bidentate fashion, an 'anti-clockwise' conformation should be more energetically favored than a 'clockwise' conformation for steric reasons, which offers a reversed S-shaped CD signal. In the case of (*R*)-2-amino-1-propanol, the 'clockwise' conformation must be more stable than the 'anti-clockwise' one to give an S-shaped CD signal. A variety of chiral amino alcohols gave chirality-dependent CD signals upon the highly coordinated complexation. Their signs were well understood by considering the bidentate coordination modes, though several stereoisomers of the resulting ternary complexes could be assumed. Such bidentate coordination probably induces asymmetric deformation of three chromophoric β-diketonate ligands in the coordination sphere of the lanthanide center to exhibit the CD signals around 300 nm.

Lanthanide tris(β-diketonates) were reported to form 1:2 highly coordinated complexes with monoalcohol or monoamine substrates in non-coordinating solvents [6a,6b], but they selectively formed ternary complexes with amino alcohols in polar solvents. Log *K* values of lanthanide complexes **2** measured in CH_3OH–CH_2Cl_2 (1/99) were 4 or 5 for amino alcohols, but 2 or less for monoalcohol, mono amine and diol substrates. The competition between substrate and solvent molecules for the coordination with lanthanide center resulted in high specificity for bidentate amino alcohols. The stability constant of the ternary complex with amino alcohol generally increases in the order $Pr^{3+} < Eu^{3+} < Gd^{3+} < Dy^{3+} \geq Ho^{3+} > Yb^{3+}$. Since the ionic radii of the lanthanide centers decrease in the order $Pr^{3+} > Eu^{3+} > Gd^{3+} > Dy^{3+} > Ho^{3+} > Yb^{3+}$ (Fig. 1), the smaller lanthanide center provides shorter and stronger coordination with amino alcohol, but larger steric repulsion between amino alcohol and β-diketonate ligands. The lanthanide tris(β-diketonates) **2** are also applicable in quantitative determination of the optical purity of various amino alcohols on a microgram scale [8b]. When the lanthanide complex **2** (M = Yb) (8.00×10^{-5} mol l^{-1}) was typically added to a CH_3OH–CH_2Cl_2 (1/99) solution of (*R*)- and (*S*)-amino alcohol mixture (8.00×10^{-4} mol l^{-1}), the CD amplitude observed and enantiomer excess percentage of the amino alcohol have a linear relationship as schemati-

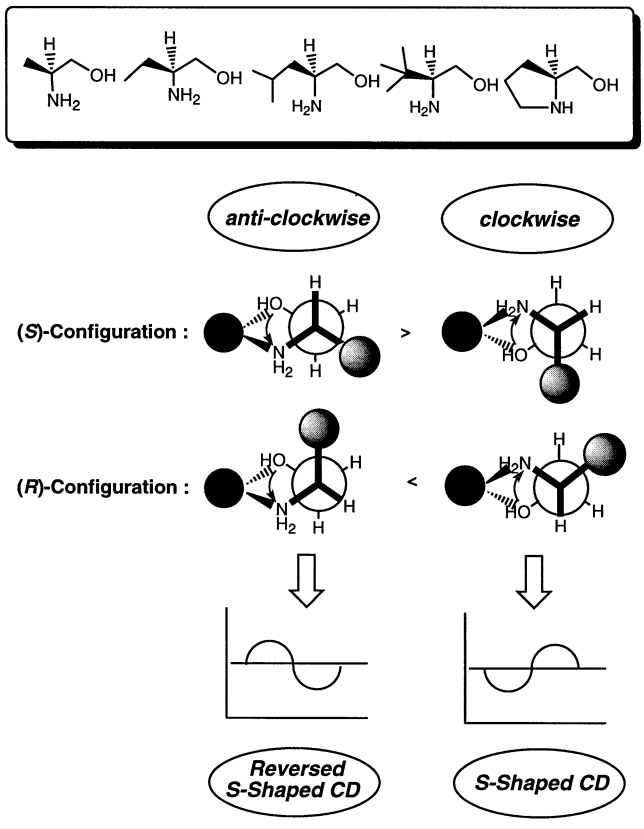


Fig. 5. Bidentate coordination from chiral amino alcohol (see Ref. [12]).

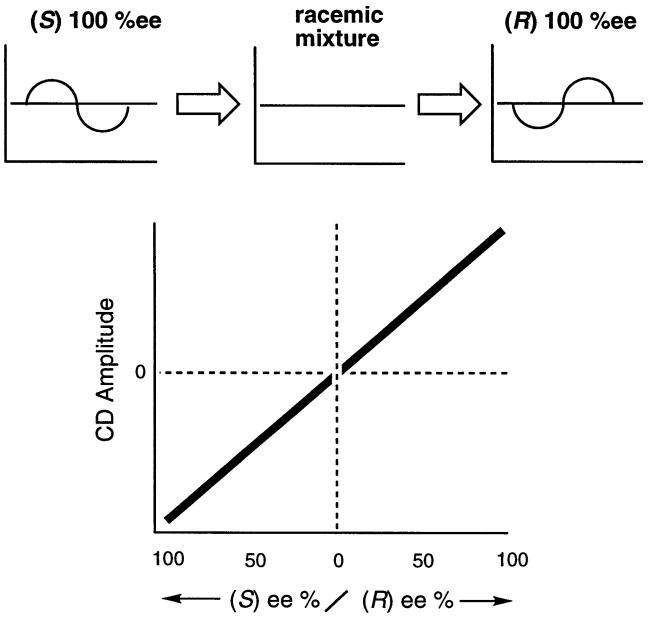


Fig. 6. Relationship between enantiomer excess percentage of amino alcohol and CD amplitude.

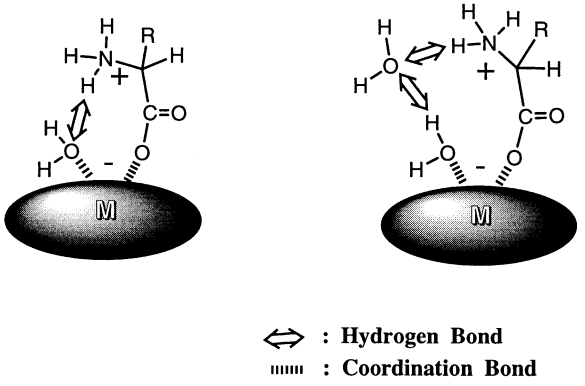


Fig. 7. Binding mode of zwitterionic amino acid with lanthanide center (see Ref. [28]).

cally illustrated in Fig. 6. Therefore, the optical purity of several micrograms of the sample can be determined using this relationship established in the CD probing system.

3. Enantiomer-selective extraction by lanthanide tris(β-diketonates)

Enantiomer recognition of a specific guest is one of the most important processes in many biological and artificial processes. A variety of synthetic receptors have been reported for chiral recognition of cationic or anionic guests, but the number of those effective for zwitterionic amino acids remains quite limited [27]. Since amino acids exist as zwitterions in neutral water and their desolvation is a costly energetic process, two or more different binding sites should be geometrically and functionally arranged in the single receptor molecule. The lanthanide tris(β-diketonates) have outstanding features as effective receptors of zwitterionic amino acids: (a) highly coordinated complexation with various substrates; (b) complex stability against hydrolysis and ligand exchange at neutral pH; and (c) substitution feasibility by chiral, fluorinated and chromophoric β-diketonate ligands.

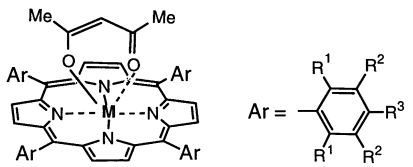
We successfully applied a series of lanthanide tris(β-diketonates) **2** in the extraction of zwitterionic amino acids [9]. The extractions were typically carried out by adding a CH_2Cl_2 solution of lanthanide tris(1,1,1,2,2,3,3-heptafluoro-7,7-dimethyl-4,6-octadionates) (**2**) (0.030 mmol/1.5 ml) to an aqueous solution of phenylalanine (0.015 mmol/1.5 ml, pH 6.2). After the mixture had been stirred for 2 h, 37–52% of the substrate was extracted into the CH_2Cl_2 solutions. Since copper bis(β-diketonate) **10**, dibenzo-18-crown-6 and other common receptors did not extract zwitterionic amino acids under neutral pH conditions, the lanthanide coordination chemistry offered efficient extraction of zwitterionic amino acids. Most of the lanthanide complexes **2** showed similar substrate selectivity of phenylalanine (Phe) > tryptophan (Trp) > leucine (Leu) > phenylglycine (PhGly). This trend appears to be more than simple hydrophobicity of the amino acid. The log *D* values of the amino acids at pH 6.2, a measure of hydrophobicity, are −1.54 for Phe, −0.70 for Trp, −1.92 for Leu and −2.22 for PhGly. Among them, Trp had the largest log *D* value (highest hydrophobicity), but its extraction percentage was lower than that of Phe. Although more hydrophilic alanine and glycine were rarely extracted, the steric factor of the guest amino acid must be considered as well as the hydrophobicity. These lanthanide tris(β-diketonates) were demonstrated to form negatively charged ternary complexes with anionic guests which were detectable by negative FAB MS method [22b]. Such anionic species can interact with the $-NH_3^+$ part of the amino acids intramolecularly via electrostatic interaction or direct hydrogen bonding between $-NH_3^+$ hydrogen and β-diketonate oxygen [9]. Aime et al. recently proposed similar hydrogen bonding modes in which the $-NH_3^+$ part of the zwitterionic amino acid was bound with lanthanide center through water molecules (Fig. 7) [28].

When camphor-derived β-diketonate, 3-(heptafluoropropylhydroxymethylene)-camphorate, was combined with trivalent lanthanide cations, zwitterionic amino acids were extracted in an enantiomer-selective fashion [9]. Both enantioselectivity and extractability were significantly dependent on the size of the lanthanide center. The extractability of the complexes **3** decreased as the lanthanide cation changed from Pr^{3+} or Eu^{3+} to Er^{3+} and then to Yb^{3+}. The enantioselectivity, in contrast, had a reversed order of $Pr^{3+} \leq Eu^{3+} < Er^{3+}$

$< Yb^{3+}$, and the highest enantiomeric excess was recorded for L-phenylglycine as 49% ee with chiral ytterbium tris[3-(heptafluoro-propylhydroxymethylene)-(+)-camphorate] **3** (M = Yb). This is an extremely high value compared with other liquid–liquid extraction systems [29] and demonstrates the practical potential of the lanthanide complex-type receptors. Since lanthanide tris[3-(trifluoromethylhydroxy–methylene)-camphorates] (**9**) offered effective extraction of amino acids with modest enantiomer selectivity (< 10% ee), the nature of the β-diketonate ligand greatly influenced enantiomer selectivity. Although the present type of lanthanide tris(β-diketonates) may have several stereoisomers in the solutions, the combination of small ytterbium ion and bulky chiral β-diketonate provided the enhanced enantioselectivity of the amino acids.

4. Chirality sensing by lanthanide porphyrinates

Some transition metal porphyrinates were presented as effective CD probes for chirality determination of neutral substrates [30]. For example, zinc porphyrinates including additional binding sites were elegantly designed to bind chiral neutral substrates at two points. Since their Soret absorption bands were strong enough to induce intense CD signals, they were applicable in the chirality detection. We demonstrated that the lanthanide porphyrinates **4** functioned as highly sensitive CD probes especially for zwitterionic amino acids [10,11]. These were electrically neutral complexes including dianionic porphyrinate and monoanionic diketonate ligands. As decribed above with lanthanide tris(β-diketonates), the lanthanide porphyrinates formed the stable ternary complexes with zwitterionic amino acids, if the lanthanide center and coordinating ligands were properly chosen.



11

R^1	R^2	R^3
H	$C(CH_3)_3$	H
H	CH_3	H
H	OCH_3	H
H	Br	H
H	OCH_3	OCH_3
OCH_3	H	OCH_3
CH_3	H	CH_3
F	F	F

Fig. 8. Lanthanide *meso*-tetraphenylporphyrinates **11**.

A series of gadolinium *meso*-tetraphenylporphyrinates **11** (M = Gd) effectively extracted zwitterionic amino acids from neutral aqueous solutions into organic solutions (Fig. 8), while corresponding zinc porphyrinates rarely extracted them [11]. The 1:1 highly coordinated complexes formed gave induced CD signals in the Soret-band regions, the signs of which were specific to the absolute stereochemistry of the bound amino acids. The extraction and CD sensing behaviors of gadolinium *meso*-tetraphenylporphyrinates **11** were largely dependent on the nature of the organic phase employed. When L-phenylglycine was employed as a substrate, benzene and toluene gave about twice the CD sensitivity as cyclohexane, hexane and petroleum ether. They operated well for a broad range of amino acids: 16 kinds of natural α-L-amino acids gave reversed S-shaped CD signals upon complexation, though only L-histidine gave S-shaped CD signals and L-aspartic acid and L-lysine were rarely extracted. Compared with the CD spectra of amino acids in aqueous solutions, ca. 50 or 100 fold amplification of the CD intensity and shift of the peak from UV to the visible region were attained with these lanthanide probes. The receptor behavior of the lanthanide porphyrinate can be fine-tuned through molecular architecture. The nature of the lanthanide center greatly influenced extraction ability toward amino acids: $Gd^{3+} > Er^{3+} > Yb^{3+}$ [10]. As described in the extraction with lanthanide tris(β-diketonates) **2**, the larger lanthanide center offered more efficient extraction and subsequent higher CD sensitivity for amino acids in the tetraphenylprophyrinate **4** systems. The substituent at the *meso*-position of the tetraphenylporphyrinate skeleton also affected both extraction efficiency and CD sensitivity. *Ortho*-substitution with methoxy and methyl groups completely suppressed the sensitivity. When chiral β-diketonate ligand was introduced into the lanthanide porphyrinate system, CD sensing of achiral amino acids was realized. Typically, godolinium complex **5** extracted achiral amino acids such as glycine and β-alanine and then offered significant CD spectral changes upon highly coordinated complexation. As discussed in the ternary complexation between amino alcohol and lanthanide tris(β-diketonates) **2**, the steric crowding around the lanthanide center may induce the asymmetric arrangement of β-diketonate and porphyrinate, resulting in the intense CD signal.

5. Sophistication of lanthanide porphyrinates

We made the structure of lanthanide porphyrinate receptors **4** more sophisticated to improve the extrac-

tion and sensing functions for specific substrates (Fig. 2) [10,31]. When zwitterionic amino acids are targeted, the effective receptors should have multiple binding sites highly complementary to the $-NH_3^+$ and $-CO_2^-$ groups of the amino acids [27]. The conjugate **6** (M = Er) was designed along this line, because benzo-18-crown-6 catches $-NH_3^+$ moiety and lanthanide porphyrinate binds $-CO_2^-$ moiety. This extracted several amino acids from neutral aqueous solution into CH_2Cl_2 solution more efficiently than the parent erbium porphyrinate **4** (M = Er): [extraction percentage by **6**]/[extraction percentage by **4**] = 48/38% for Phe; 40/18% for Trp. Thus, the amino acids were cooperatively bound by erbium porphyrinate and 18-crown-6 ring. After extraction experiments with L-amino acids, this conjugate gave reversed S-shaped CD bands at the Soret-band region, while it offered S-shaped CD bands for D-isomers. The gadolinium- and ytterbium-containing conjugates **6** (M = Gd and Yb) gave similar extraction efficiencies and CD sensitivities to those of parent porphyrinates **4**. Therefore, the nature of the lanthanide center significantly influences on the probe functions of conjugate-type receptors.

The conjugate **6** (M = Er) also acted as an effective receptor of the biogenetic amine salts tyramine, serotonin and noradrenaline salts [31]. These biogenetic amines were extracted not only from neutral aqueous solution (pH 6.0), but also from acidic aqueous solution (pH 3.6), suggesting that the biogenetic amines were bound as monocationic forms. Although the 'conjugate effects' were clearly observed in the extraction of these biogenetic amines, the CD signals induced around Soret-band regions were too weak to be used in the chirality determination. The employed biogenetic amines have two kinds of binding sites: (i) phenol or catechol moiety for coordination with the erbium center; and (ii) ammonium cation pointing towards the crown ring. Since the former binding site is located apart from the asymmetric center, the conjugate was thought to work as an effective receptor but an insensitive CD probe.

The conjugation of lanthanide porphyrinate with 18-crown-6 ring significantly enhanced extraction abilities of biological substrates and also provided new sensitive CD chirality probing. The 'conjugate strategy' based on lanthanide porphyrinates has various extensions. Double-decker and dimer derivatives **7** and **8** are promising candidates (Fig. 2). The double-deckers including Ce^{4+} ion bound dicarboxylate substrates and exhibited induced CD signals [32]. Since the porphyrine dimers containing Zn^{2+} ion also acted as sensitive CD probes [33], more sophisticated lanthanide porphyrinates offer more effective receptors for sensing, transport and separation of other biological substrates.

6. Conclusion

This review has described that lanthanide tris(β-diketonates) and porphyrinates offered interesting chiral recognition and chirality sensing of the biological substrates such as amino acids and biogenetic amines. Based on their 'exotic' coordination chemistry, they exhibited unique receptor characteristics in extraction and chirality sensing. The lanthanide tris(β-diketonates) caused broadening of NMR signals of various biological substrates in a non-selective sense, but optimization of their structures and conditions improved the receptor functions. Furthermore, the introduction of chiral fluorinated ligands in the lanthanide tris(β-diketonates) offered satisfactorily high enantiomer-selective extraction of zwitterionic amino acids, while the lanthanide porphyrinates and their conjugate derivatives attained precise chirality sensing of the biological substrates.

The lanthanide complexes have further potential as specific receptors of biopolymers. Some of them are known as hydrolytic catalysts in protein and gene technology. The quenching phenomena between luminescent lanthanide complexes with biopolymers were extensively investigated [34]. Therefore, further structural optimization of these complexes may provide promising possibilities in the development of specific recognition and sensitive sensing of various chiral substrates of biological interest.

Acknowledgements

The authors express their thanks to Professors Jun'ichi Uenishi (Kyoto Pharmaceutical University) and Osamu Yonemitsu (Okayama University of Science) for cooperative investigations. Permissions to use Figures 4, 5 and 7 which were granted by American Chemical Society and Royal Society of Chemistry are appreciated. This work was supported in part by a Grant-in-Aid for Scientific Research (No.10440198) from the Japan Society for the Promotion of Science.

References

[1] Recent reviews on lanthanide coordination chemistry: (a) S. Aime, M. Botta, M. Fasano, E. Terreno, Chem. Soc. Rev. 27 (1998) 19;
(b) C. Piquet, J.-C.G. Bünzli, Chem. Soc. Rev. 28 (1999) 347;
(c) P. Caravan, J.J. Ellison, T.J. McMurry, R.B. Lauffer, Chem. Rev. 99 (1999) 2293.
[2] D.J. Raber, in: T.C. Morril (Ed.), Lanthanide Shift Reagents in Stereochemical Analysis, VCH, New York, 1986.
[3] T. Imamoto, Lanthanides in Organic Synthesis, Academic Press, London, 1994.
[4] (a) G.E. Buono-Core, H. Li, Coord. Chem. Rev. 99 (1990) 55;
(b) H.G. Brittain, Chirality 8 (1996) 357;
(c) M.J. Heeg, S.S. Jurisson, Acc. Chem. Res. 32 (1999) 1053;

(d) D. Parker, M. Botta, M. Fasano, E. Terreno, Coord. Chem. Rev. 205 (2000) 109.
[5] R.D. Shanoon, Acta Crystallogr. Sect. A 32 (1976) 751.
[6] Several kinds of highly coordinated complexes between lanthanide tris(β-diketonates) and organic substrates were isolated and their crystal structures were reported. For monodentate substrates: (a) J.A. Cunningham, R.E. Sievers, Inorg. Chem. 19 (1980) 595;
(b) L.A. Laplanche, G. Vanderkooi, J. Chem. Soc. Perkin Trans. II (1983) 1585;
For bidentate substrates: (c) I. Baxter, S.R. Drake, M.B. Hursthouse, K.M.A. Malik, J. McAleese, D.J. Otway, J.C. Plakatouras, Inorg. Chem. 34 (1995) 1384;
(d) H.J. Batista, A.V.M. de Andrade, R.L. Longo, A.M. Simas, G.F. de Sa, N.K. Ito, L.C. Thompson, Inorg. Chem. 37 (1998) 3542.
[7] (a) T.J. Meade, R.A. Moats, S.E. Fraser, Angew. Chem. Int. Ed. Engl. 36 (1997) 726;
(b) T. Gunnlaugsson, D.A. MacDonail, D. Parker, Chem. Commun. (2000) 93.
[8] Reviews: (a) H. Tsukube, S. Shinoda, Bol. Soc. Chil. Quim. 42 (1997) 237;
(b) H. Tsukube, S. Shinoda, Enantiomer 5 (2000) 13.
[9] H. Tsukube, S. Shinoda, J. Uenishi, T. Kanatani, H. Itoh, M. Shiode, T. Iwachido, O. Yonemitsu, Inorg. Chem. 37 (1998) 1585.
[10] H. Tsukube, M. Wada, S. Shinoda, H. Tamiaki, Chem. Commun. (1999) 1007.
[11] H. Tamiaki, N. Matsumoto, S. Unno, S. Shinoda, H. Tsukube, Inorg. Chim. Acta 300–302 (2000) 243.
[12] H. Tsukube, M. Hosokubo, M. Wada, S. Shinoda, H. Tamiaki, Inorg. Chem. 40 (2001) 740.
[13] (a) K. Nakanishi, J. Dillon, J. Am. Chem. Soc. 93 (1971) 4058;
(b) J. Dillon, K. Nakanishi, J. Am. Chem. Soc. 97 (1975) 5417.
[14] (a) N.H. Andersen, B.J. Bottino, A. Moore, J.R. Shaw, J. Am. Chem. Soc. 96 (1974) 603;
(b) G.N. Mitchell, F.I. Carrall, J. Am. Chem. Soc. 95 (1973) 7912;
(c) C. Lyons, D.R. Taylor, J. Chem. Soc. Chem. Commun. (1976) 647;
(d) B. Wegrzynski, V. Toome, Anal. Lett. (1991) 317;
(e) V. Toome, B. Wegrzynski, Amino Acids 3 (1992) 195;
(f) B. Dayal, K. Rao, G. Salen, W.M. Seong, B.N. Pramanik, E.C. Huang, V. Toome, Pure Appl. Chem. 66 (1994) 2037;
(g) D.H. Metcalf, J.P. Bolender, M.S. Driver, F.S. Richardson, Other type of CD probe: J. Phys. Chem. 97 (1993) 553.
[15] H.G. Brittain, J. Chem. Soc. Dalton (1984) 1367.
[16] E. Huskowska, J.P. Riehl, Inorg. Chem. 34 (1995) 5615.
[17] J.I. Bruce, R.S. Dickins, L.J. Govenlock, T. Gunnlaugsson, S. Lopinski, M.P. Lowe, D. Parker, R.D. Peacock, J.I.B. Perry, S. Aime, M. Botta, J. Am. Chem. Soc. 122 (2000) 9674.
[18] T.I. Wenzel, R.E. Silvers, J. Am. Chem. Soc. 104 (1982) 382.
[19] (a) C.-P. Wong, R.F. Venteicher, W.D. Horrocks, J. Am. Chem. Soc. 96 (1974) 7145;
(b) J.L. Sessler, G. Hemmi, T.D. Mody, T. Murai, A. Burrell, S.W. Young, Acc. Chem. Res. 27 (1994) 43.
[20] H. Ogoshi, T. Mizutani, Acc. Chem. Res. 31 (1998) 81.
[21] S. Radzki, C. Giannotti, Inorg. Chim. Acta 205 (1993) 213.
[22] (a) H. Tsukube, H. Shiba, J. Uenishi, J. Chem. Soc. Dalton (1995) 181;
(b) H. Tsukube, J. Uenishi, H. Shiba, O. Yonemitsu, J. Membr. Sci. 114 (1996) 187;
(c) H. Tsukube, S. Shinoda, J. Uenishi, M. Shiode, O. Yonemitsu, Chem. Lett. (1996) 969.
[23] Transport of amino acids as cationic forms: (a) I. Willner, Y. Eichen, S. Sussan, B. Shoham, New J. Chem. 15 (1991) 879;
(b) H. Tsukube, J. Uenishi, H. Higaki, K. Kikkawa, Chem. Lett. (1992) 2307.
[24] (a) F.S. Richardson, Chem. Rev. 82 (1982) 541;
(b) N. Berova, K. Nakanishi, R.W. Woody (Eds.), Circular Dichroism: Principles and Applications, Wiley-VCH, New York, 2000.
[25] Examples of CD probes: (a) Y. Kikuchi, K. Kobayashi, Y. Aoyama, J. Am. Chem. Soc. 114 (1992) 1351;
(b) T. Morozumi, S. Shinkai, J. Chem. Soc. Chem. Commun. (1994) 1219;
(c) M. Crossley, L.G. Mackay, A.C. Try, J. Chem. Soc. Chem. Commun. (1995) 1925;
(d) T. Mizutani, T. Kurahashi, T. Murakami, N. Matsumi, H. Ogoshi, J. Am. Chem. Soc. 119 (1997) 8991;
(e) E. Yashima, T. Natsusihima, Y. Okamoto, J. Am. Chem. Soc. 119 (1997) 6345;
(f) X. Huang, B.H. Rickman, B. Borhan, N. Berova, K. Nakanishi, J. Am. Chem. Soc. 120 (1998) 6185.
[26] (a) S.W. Graves, J.A. Fox, B.M. Babior, Biochemistry 19 (1980) 3630;
(b) T. Shibata, T. Takahashi, T. Konishi, K. Soai, Angew. Chem. Int. Ed. Engl. 36 (1997) 2458;
(c) T. Schrader, J. Org. Chem. 63 (1998) 264.
[27] Reviews: (a) M.T. Reetz, in: F. Voegtle (Ed.), Comprehensive Supramolecular Chemistry, vol. 2, Pergamon Press, Oxford, 1996, p. 553;
Examples: (b) P.D. Beer, M.G.B. Drew, R.J. Knubley, M.I. Ogden, J. Chem. Soc. Dalton Trans. (1995) 3117;
(c) M.F. Paugam, J.T. Bien, B.D. Smith, L.A. Chrisstoffels, F. Jong, D.N. Reinhoudt, J. Am. Chem. Soc. 118 (1996) 9820;
(d) D.T. Rosa, D. Coucouvanis, Inorg. Chem. 37 (1998) 2328;
(e) J.L. Sessler, A. Andrievsky, Chem. Eur. J. 4 (1998) 159.
[28] S. Aime, M. Botta, J.I. Bruce, V. Mainero, D. Parker, E. Terreno, Chem. Commun. (2001) 115.
[29] A. Metzger, K. Gloe, H. Stepkan, F.P. Schmidtchen, J. Org. Chem. 61 (1996) 2051.
[30] (a) Y. Aoyama, M. Asakawa, A. Yamagishi, H. Toi, H. Ogoshi, J. Am. Chem. Soc. 112 (1990) 3145;
(b) T. Mizutani, T. Ema, T. Yoshida, T. Renne, H. Ogoshi, Inorg. Chem. 33 (1994) 3558;
(c) H. Tamiaki, A. Kiyomori, K. Maruyama, Bull. Chem. Soc. Jpn. 67 (1994) 2478.
[31] H. Tsukube, M. Wada, S. Shinoda, H. Tamiaki, J. Alloy Comp. 323–324 (2001) 133.
[32] (a) K. Tashiro, K. Konishi, T. Aida, Angew. Chem. Int. Ed. Engl. 36 (1997) 856;
(b) A. Sugasaki, M. Ikeda, M. Takeuchi, S. Shinkai, Angew. Chem. Int. Ed. Engl. 37 (1998) 2096.
[33] (a) X. Hung, B. Borham, B.H. Rickman, K. Nakanishi, N. Berova, Chem. Eur. J. 6 (2000) 210;
(b) V.V. Borovkov, J.M. Lintuluoto, M. Fujiki, Y. Inoue, J. Am. Chem. Soc. 122 (2000) 4403.
[34] (a) D.H. Metcalf, J.M.McD. Stewart, S.W. Snyder, C.M. Grisham, F.S. Richardsons, Inorg. Chem. 31 (1992) 2445;
(b) S.C.J. Meskers, M. Ubbink, G.W. Canters, H.P.J.M. Dekkers, J. Phys. Chem. 100 (1996) 17957.