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Alkoxy bridged binuclear rhenium (I) complexes as a potential sensor for β-amyloid aggregation

Veerasamy Sathish [a,c], Eththilu Babu [a,d], Arumugam Ramdass [a], Zong-Zhan Lu [b], Murugesan Velayudham [b], Pounraj Thanasekaran [b,*], Kuang-Lieh Lu [b,*], Seenivasan Rajagopal [a,**]

[a] School of Chemistry, Madurai Kamaraj University, Madurai 625 021, India
[b] Institute of Chemistry, Academia Sinica, Taipei 115, Taiwan
[c] Department of Chemistry, Bannari Amman Institute of Technology, Sathyamangalam, India
[d] Department of Chemistry, V.V. College of Engineering, Tisayanvilai, Tirunelveli, India

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ABSTRACT

Alkoxy bridged binuclear rhenium(I) complexes are used as a probe for the selective and sensitive detection of aggregation of β-amyloid fibrils that are consorted with Alzheimer's disease (AD). The strong binding of the complexes is affirmed by the fluorescence enhancement and calculated binding constant value in the order of $10^5\ M^{-1}$ is obtained from the Scatchard plots. The binding of β-amyloid can be attributed to π−π stacking interaction of naphthalene moiety present in rhenium(I) complexes, and it is supported by docking studies. The selectivity is quite high towards other proteins and the formation of fibrils can be observed in the range of 30–40 nm through the AFM and TEM techniques.

1. Introduction

Alzheimer's disease (AD) [1–4] is a calamitous neurodegenerative disorder caused by aggregation of amyloid-β (Aβ) peptides and the aggregation leads to the formation of the senile plaques (amyloid plaques), neurofibrillary 'tangles,' in the brain. In USA, 39 million people are affected by AD and this figure will soar greater than twofold to 89 million by 2050; AD is a growing threat to developing countries [5]. β-Amyloid aggregates are highly organized protein filaments, rich in β-sheet secondary structure, generated by the amyloid-β precursor protein (APP), which is cleaved by γ-secretase to create amyloid-β, and two forms of presenilin [6,7]. Though the etiology is controversial and immunotherapy trials are continuing, no drug has been invented so far to delay or stop the β-amyloid accumulation hitherto. However, the hypothesis of amyloid cascade has been reported recently by several groups [8,9]. After using the positron emission tomography (PET) to identify amyloid plaques in the brain, the research on early detection of amyloid aggregate formation using different techniques is spurred to the diagnosis of the disease [10].

Congo Red (CR) [10–14]and thioflavin T (ThT) [15–17], two classical dyes displaying intriguing photophysical properties, have been used extensively for the detection and sensing of amyloid fibrils. Recently a number of studies have been reported on the application of dyes other than CR and ThT that have been used as sensitive probes for detection of amyloid fibrils [18–21]. Apart from the organic dyes, metal complexes have also been used as sensors for the amyloid aggregates [22–25]. Marti [26] and Rangachari [27] have used ruthenium(II) complex as a sensor and inhibitor of the activity of β-amyloid aggregation. Apart from ruthenium, copper(II) complex [28] and radio-labeled metal complexes such as rhenium and technetium have potential application towards the radiodiagnostic imaging of β-amyloid plaques [29,30]. Recent developments on stilbene-based probes show that they are potential candidates for the binding and diagnosis of Aβ plaques [31–33]. In the present study, we have synthesized and characterized two alkoxy bridged binuclear rhenium(I) complexes containing long alkyl chains with photoisomerizable 4-(1-naphthylvinyl) pyridine ligand (1,4-NVP). It is noteworthy that the ligand 1,4-NVP has stilbene-like structure and properties. These metal complexes carrying *trans* isomer of 1,4-NVP ligand have remarkable photoswitching properties under irradiation of UV light with the ability to serve as a probe for biomolecules as well as for optical imaging [34]. Further, the aggregation of long alkyl chains leads to aggregation induced emission enhancement (AIEE) properties

* Corresponding authors. Tel.: +886 2 27898518; fax: +886 2 27831237.
** Corresponding author. Tel.: +91 452 2458246; fax: +91 452 2459139.
E-mail addresses: ptsekaran@yahoo.com (P. Thanasekaran), kllu@gate.sinica.edu.tw (K.-L. Lu), rajagopalseenivasan@yahoo.com (S. Rajagopal).

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[35]. To the best of our knowledge, this is the first report on rhenium(I) binuclear complex carrying stilbene-like ligand finding application as a sensor for formation of amyloid fibrils. The structure of these complexes is shown in Chart 1.

2. Experimental

2.1. Methods and materials

The bimetallic rhenium(I) complexes **1** and **2** were synthesized by a one pot self-assembly method from $Re_2(CO)_{10}$ and 4-(1-naphthylvinyl)pyridine in 1-butanol or 1-decanol and characterized by various spectral techniques [34]. Amyloid-β protein was purchased from CALBIOCHEM. Emission intensity measurements were carried out and the emission spectra were recorded using a JASCO FP-6300 spectrofluorimeter. Excitation and emission slits with a band-pass of 5 nm were used for all measurements. HPLC grade DMSO and MilliQ water was used for each measurement. All measurements were carried out under room temperature. Transmission electron microscopy (TEM) analysis was performed on a Tecnoi-10-Philips instrument at 80 kV accelerating voltage. The AFM image was obtained on a PicoPlus AFM instrument (Molecular Imaging Inc., Arizona, USA) operating in the noncontact mode. AFM images were taken under dry condition. The NCL cantilever was used to scan the sample at a frequency of 177 kHz and a scanning speed 2.4 lines/s. A solution (1 μM) of Re (I) complexes **1** and **2** (98% H_2O–2% DMSO (v/v)) was incubated with amyloid monomer (0–12 μM) and agitated for an hour to carry out the fluorescence measurements with amyloid fibrils and then the fluorescence change was measured by excitation of the probe at 350 nm.

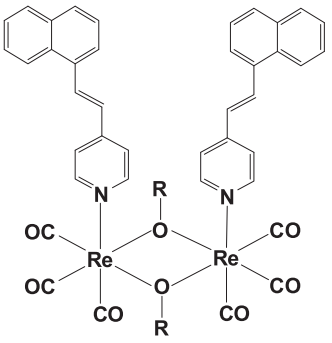

Chart 1. The structure of two alkoxy bridged binuclear Re(I) complexes **1** and **2**.

2.2. Calculation of binding constant

The data on the luminescence intensity change of Re(I) complex in the presence of amyloid-β are subjected to analysis using the Scatchard plots [36,37] (Eq. 1) to determine the binding constant of the probe with the protein:

$$\nu/[\mathrm{Re}]_{\mathrm{free}} = n\mathrm{Ka} - \nu\,\mathrm{Ka} \quad (1)$$

Here, $\nu = [\mathrm{Re}]_{\mathrm{bound}}/[\mathrm{amyloid}]$, n is the binding stoichiometry, [amyloid] is the concentration of the amyloid and $[\mathrm{Re}]_{\mathrm{bound}}$ is the concentration of the bound form of the complex. $[\mathrm{Re}]_{\mathrm{bound}}$ was calculated using the equation

$$[\mathrm{Re}]_{\mathrm{bound}} = [\mathrm{Re}]_{\mathrm{total}} - [\mathrm{Re}]_{\mathrm{free}} \quad (2)$$

$$[\mathrm{Re}]_{\mathrm{free}} = [\mathrm{Re}]_{\mathrm{total}}\{[(I/I_0) - P]/(1-P)\} \quad (3)$$

Here $[\mathrm{Re}]_{\mathrm{total}}$ and $[\mathrm{Re}]_{\mathrm{free}}$ are the total and free concentration of the Re(I) complex, I and I_0 are emission intensity of the complex in the presence and absence of amyloid, respectively, and P is $\max(I/I_0)$, which can be obtained as $1/(y\text{-intercept})$ from the linear plot of I_0/I *vs* $[\mathrm{amyloid}]^{-1}$.

2.3. Docking studies of amyloid protein with Re(I) complexes

The pdb (protein data bank) files of protein molecules were downloaded from protein data bank (http://www.rcsb.org/pdb/home/home.do). β-Amyloid (PDB ID: 1Z0Q) was chosen as the initial structure. The final model chosen was minimized using DISCOVER module of InsightII with 1000 rounds of steepest descent and 1000 rounds of conjugate minimization. The cavity of the protein model has been picked by using Computed Atlas of Surface Topography of Proteins (CASTp). The docking towards the luminophores such as tryptophan and tyrosine has been done using GOLD [38]. For viewing the docked solutions and to generate pictures, UCSF Chimera candidate version 1.5.3 is used [39].

3. Results and discussion

3.1. Luminescence titrations

Luminescence titration experiments have been carried out in order to demonstrate the binding of complexes **1** and **2** with

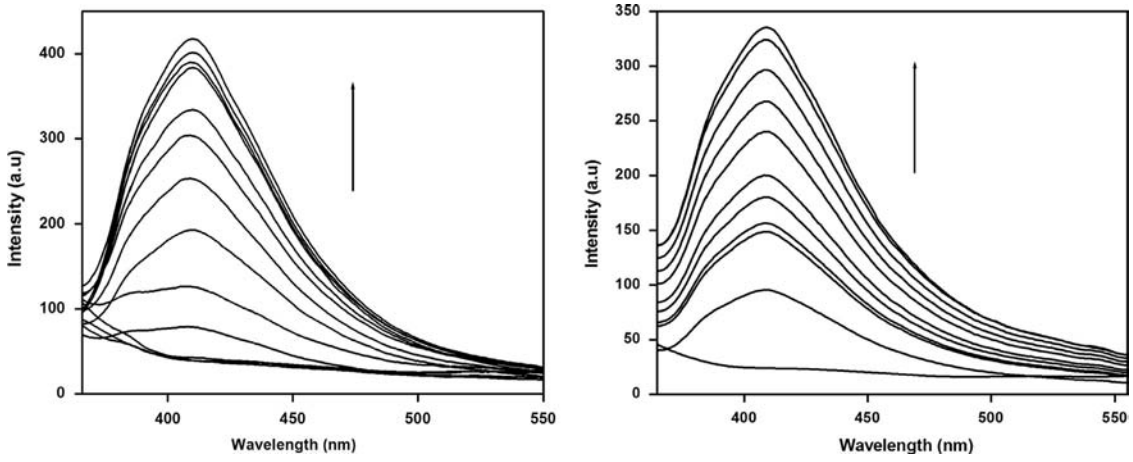

Fig. 1. The luminescence titration spectra of complexes **1** and **2** with various concentrations of amyloid fibrils. The concentrations of complex and amyloid-β are 1×10^{-6} M and 0–12 μM respectively.

amyloid fibrils and the titration spectra are shown in Fig. 1. In the presence of amyloid-β fibrils, the luminescence intensity gradually increases due to the strong binding of Re(I) complex with the hydrophobic packet of amyloid-β fibrils. In addition the luminescence maximum is blue-shifted from 440 to 413 nm along with luminescence enhancement, suggesting that the probe is surrounded by more nonpolar environment of amyloid-β fibrils. These results clearly point out the interaction of Re(I) complexes with amyloid-β fibrils and this observation is similar to the light switching behavior of ruthenium complexes with DNA [40–42]. The increase in intensity of probe can be due to the progressive binding of the probe with amyloid protein and this makes nonradiative channels present in aqueous medium less operative inside the amyloid fibrils. The naphthalene moiety in these Re (I) complexes may strongly interact with amyloid protein through $\pi-\pi$ stacking interaction [43,44]. It is expected that the parallel orientation of βsheet structures generates small channels and hydrophobic pockets that extend along the length of the filament to which aromatic molecules can intercalate and bind through the $\pi-\pi$ interaction. But these compounds contain a stilbene-like component, which is a highly conjugated rigid aromatic ring system, having a potential to display the highest affinity toward Aβ fibrils. Hence, it is proposed that these Re(I) complexes carrying 1,4-NVP ligand enter a hydrophobic pocket and bind with the protein through $\pi-\pi$ stacking interactions [45]. The detection limit of the sensing β-amyloid is found to be 2.0 μM and the fluorescence increases by ~eight orders of magnitude in the presence of fibrils, which find good agreement with those of other probes [26,28]. The Re(I) complex shows poor luminescence intensity in the absence of amyloid-β protein. After an hour, protein aggregation starts with the formation of small fibril aggregates which act as seeds for the further assembly of amyloid-β monomers into aggregated fibrillar structures. This aggregation and fibril elongation phase is relatively fast followed by a leveling off of the fluorescence once most of the monomers have been assembled into fibrils.

3.2. Determination of binding constant

Scatchard plots for the binding of complexes **1** and **2** with amyloid-β fibrils are presented in Fig. 2. A straight line with a positive slope indicates that the proportion of rhenium complex that binds with amyloid increases with increasing concentration of amyloid-β [46]. The binding constants are $2.2\times10^5\ M^{-1}$ and $2.0\times10^5\ M^{-1}$, respectively, for complexes **1** and **2**.

Sulatskaya et al. [47,48] reported that two binding modes were found for the interaction of ThT with amyloid fibrils. The nonlinearity of Scatchard plots obtained for the binding of ThT to amyloid fibrils suggests that more than one binding mode is available with significantly different binding constants. In our case, the linear plot obtained from Scatchard plot points to only one binding mode and this is in agreement with the previous reports [47,48].

3.3. Selectivity

We added 1 μM of each sample of some common extracellular proteins such as lysozyme, BSA, PDGF, thrombin, myoglobin, hemoglobin and cytochrome C to the probe solution to confirm the selectivity of amyloid binding probe towards amyloid. Significant luminescence intensity change is observed in the presence of amyloid compared to other proteins, revealing that the probe is selective towards amyloid protein and it may be due to more hydrophobic than other proteins and the results are shown in Fig. 3.

3.4. Detection of amyloid fibrils

Atomic force microscopy (AFM) is employed to analyze the formation of β-amyloid fibrils and it is also used to determine the morphological parameters such as height and length of the fibrils [49]. After the incubation period, the samples of amyloid-β are deposited on freshly cleaved mica surfaces and the images are collected at different micrometer areas of amyloid fibrils using the tapping mode AFM technique [50,51]. For preparation of fibrils, we adapt the previously reported procedures [52,53]. The Aβ peptide is dissolved in a minimum amount of 2 mM NaOH and the pH is adjusted to 10.5 using 100 mM NaOH. The peptide solution is sonicated for 2 min, and then filtered. The filtered solution is adjusted to 400 μL using sodium phosphate buffer. The samples were incubated at 37 °C and the fibril formation of Aβ with complex **2** was monitored.

The AFM images show the formation of amyloid fibrils with a size of 30–40 nm from the aliquots of amyloid samples with complex **2** after 3 h (Fig. 4). These results indicate that the luminescence enhancement of Re(I) binuclear complex **2** is due to amyloid fibril formation and thus **2** can serve as a sensor for the formation of amyloid fibrils without inhibition. Furthermore, the formation of these amyloid fibrils can be confirmed by the transmission electron microscopy (TEM). For TEM, 10 μL solution of **2** was taken directly from monitored Aβ samples (complex **2**

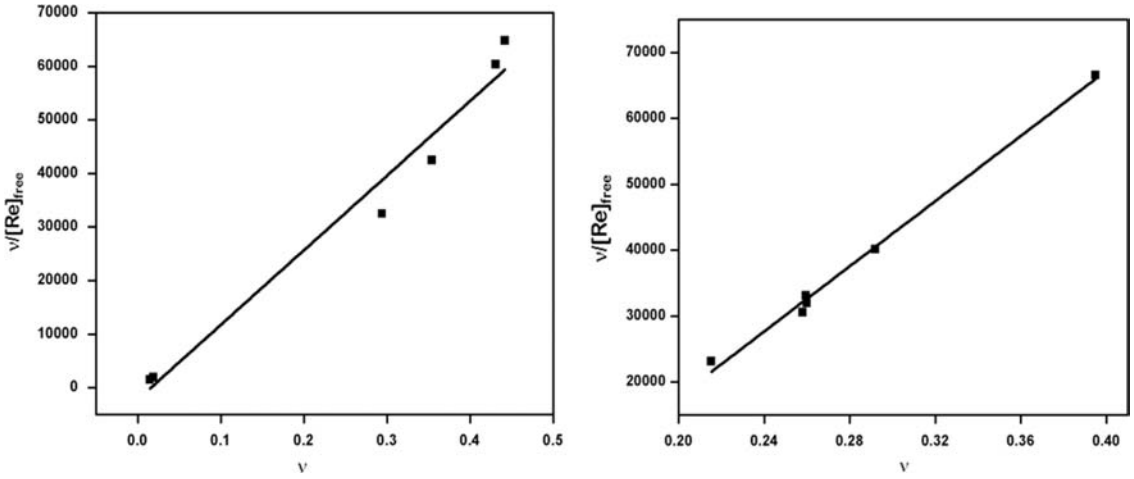

Fig. 2. Scatchard plots for complexes **1** and **2** in the presence of Aβ.

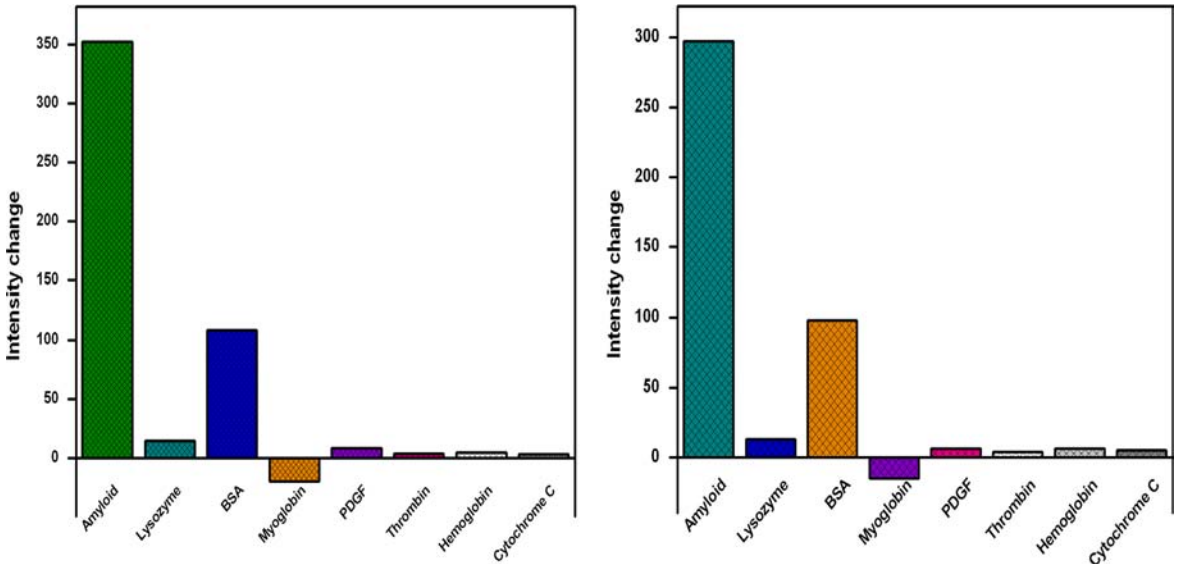

Fig. 3. The selectivity of complexes **1** and **2** based Aβ towards other proteins.

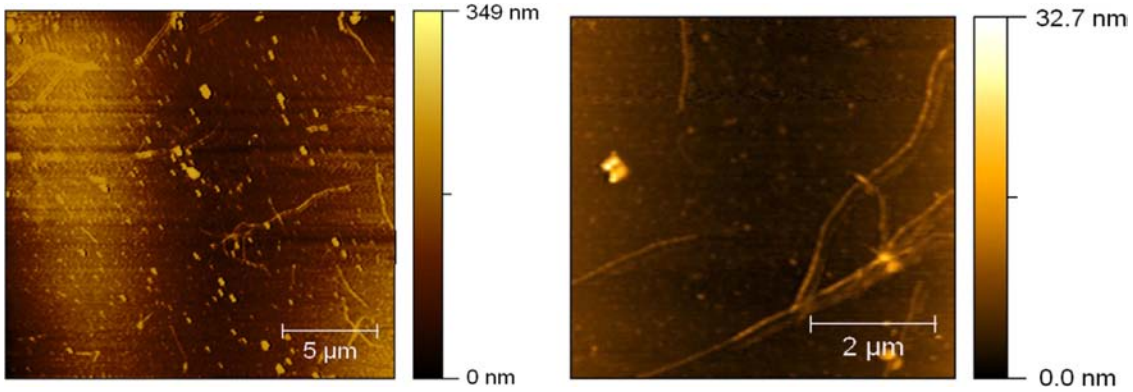

Fig. 4. The AFM images of amyloid fibrils with different magnifications.

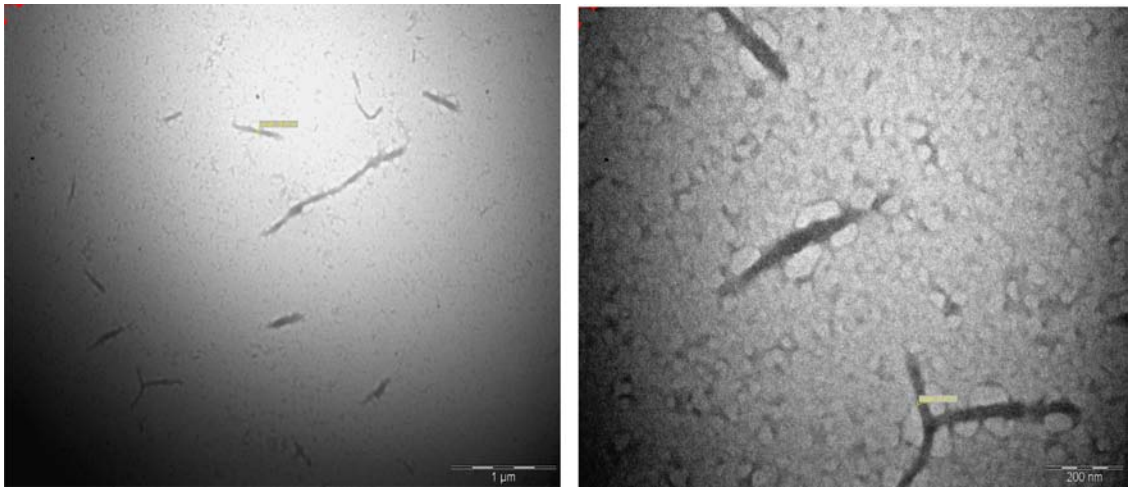

Fig. 5. TEM images with different magnifications of amyloid fibrils in the presence of complex **2** after 30 min.

with fibrillar Aβ). It is confirmed that the formation of fibrils apparently results from self-aggregation of the Aβ monomers with a size of 40 nm (Fig. 5). Recently Waldauer et al. [54] reported that when the azobenzene is in *trans* form the fibril formation has well organized structure, whereas in *cis* conformer the morphologies are distorted. The sample was intermittently illuminated by UV-light, which switched the photolinker into the *cis* state; the fibrils were induced to dissociate and then allowed to associate when the illumination was removed. The samples of *trans* isomer taken after reaggregation contain fibrils identical to those observed following the initial aggregation step, which means that the fibrils are stable in the *trans* isomer. In the presence of Re(I) complexes, the *trans*

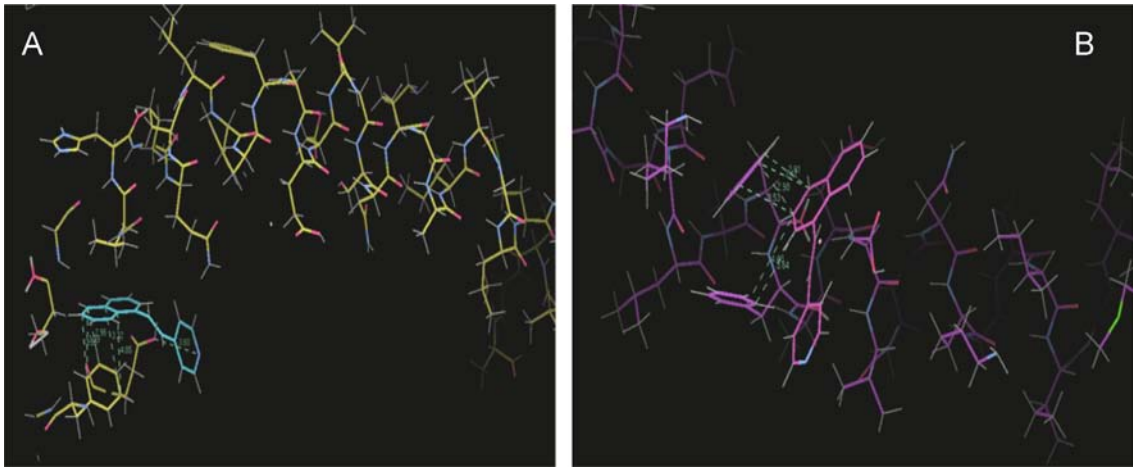

Fig. 6. Different docking poses of the 1,4-NVP ligand in complexes with the phenylalanine moiety in β-amyloid protein.

isomer of the 1,4-NVP ligand binds to the amyloid protein and the formation of amyloid fibrils is observed rather than the inhibiting/deaggregating fibrils.

To gain more knowledge on binding efficiency and to know about the mode of binding, docking studies were attempted. Since the study involves luminescence technique and monitoring the luminescence change experimentally, we identify the fluorophore inside the cavity. Since the protein comprises tryptophan, tyrosine and phenyl alanine amino acid units, we have chosen the PHE 19 and PHE 4 in β-amyloid protein which is available inside the cavity to identify the nature of binding and the docked structures are shown in Fig. 6. [55,56]. The 1,4-NVP ligand of the Re(I) complexes is considered as a model for docking with the amyloid protein and fits inside the hydrophobic cavity of protein. It is evident that the distance between naphthyl moiety of the 1,4-NVP ligand and the interacting sites of the proteins PHE 19 and PHE 4 is 2.98–4.43 Å and 2.96–4.01 Å, respectively. These results exhibit that the presence of π-electron cloud in naphthalene moiety in 1,4-NVP ligand can interact with the benzene ring in phenylalanine *viz*. PHE 19 and PHE 4 through $\pi-\pi$ stacking interactions. Obviously, it is clear that the nearby fluorophore of the protein and the ligand of the complex are very close together along with $\pi-\pi$ stacking interactions.

4. Conclusion

The Re(I) binuclear complexes can be used as a probe for the detection of amyloid fibril formation due to their very strong fluorescence enhancement upon interacting with amyloid fibrils. The strong fluorescence enhancement observed upon binding of the amyloid fibrils arises from combination of hydrophobic and $\pi-\pi$ stacking interactions. This system shows selective sensing and stronger binding activity toward the aggregated form of the protein. Using the Re(I) binuclear complex the binding activity toward Aβ aggregates and formation of the amyloid fibrils are confirmed by fluorescence spectral techniques and further by AFM and TEM techniques. The docking studies showed a strong binding of naphthalene moiety in the 1,4-NVP ligand of Re(I) complexes with the fluorophore of amyloid protein by $\pi-\pi$ stacking interactions. In addition, it is expected that application of the present result can be extended to the diagnostics of aggregates of amyloid by imaging and inhibition by aptamer-based rhenium metal complex and the work is under progress.

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References

[1] A. Abbott, Nature 475 (2011) S2–S4.
[2] F. Chiti, C.M. Dobson, Annu. Rev. Biochem. 75 (2006) 333–366.
[3] C.M. Dobson, Nature 426 (2003))884–890.
[4] D.J. Selkoe, Nature 426 (2003) 900–904.
[5] G. Stix, Sci. Am. 302 (2010) 51–57.
[6] L. Bertram, C.M. Lill, R.E. Tanzi, Neuron 68 (2010) 270–281.
[7] I.W. Hamley, Chem. Rev. 112 (2012) 5147–5192.
[8] J.A. Hardy, G.A. Higgins, Science 256 (1992) 184–185.
[9] E. Karran, M. Mercken, B.D. Strooper, Nat. Rev. 10 (2011) 698–712.
[10] W.E. Klunk, Ann. Neurol. 55 (2004) 306–319.
[11] H. LeVine III, Amyloid 12 (2005) 5–14.
[12] Y. Erez, Y.-H. Liu, N. Amdursky, D. Huppert, J. Phys. Chem. A 115 (2011) 8479–8487.
[13] P.K. Singh, M. Kumbhakar, H. Pal, S. Nath, Phys. Chem. Chem. Phys. 13 (2011) 8008–8014.
[14] N. Amdursky, Y. Erez, D. Huppert, Acc. Chem. Res. 45 (2012) 1548–1557.
[15] P.K. Singh, M. Kumbhakar, H. Pal, S. Nath., J. Phys. Chem. B 114 (2010) 2541–2546.
[16] P.K. Singh, M. Kumbhakar, H. Pal, S. Nath., J. Phys. Chem. B 114 (2010) 5920–5927.
[17] V. Fodera, M. Groenning, V. Vetri, F. Librizzi, S. Spagnolo, C. Cornett, L. Olsen, M. van de Weert, M. Leone, J. Phys. Chem. B 112 (2008) 15174–15181.
[18] C.C. Kitts, T.B. Somfai, B. Norden, Biochemistry 50 (2011) 3451–3461.
[19] S.T. Ngo, M.S. Li, J. Phys. Chem. B 116 (2012) 10165–10175.
[20] X. He, H.M. Park, S.-J. Hyung, A.S. DeToma, C. Kim, B.T. Ruotolo, M.H. Lim, Dalton Trans. 41 (2012) 6558–6566.
[21] K. Cao, M. Farahi, M. Dakanali, W.M. Chang, C.J. Sigurdson, E.A. Theodorakis, J Yang, J. Am. Chem. Soc. 134 (2012) 17338–17341.
[22] P.J. Crouch, K.J. Barnham, Acc. Chem. Res. 45 (2012) 1604–1611.
[23] I. Sasaki, C. Bijani, S. Ladeira, V. Bourdon, P. Faller, C. Hureau, Dalton Trans. 41 (2012) 6404–6407.
[24] F.B. ElGarah, C. Bijani, Y. Coppel, P. Faller, C. Hureau, Inorg. Chem. 50 (2011) 9024–9030.
[25] G. Eskici, P.H. Axelsen, Biochemistry 51 (2012) 6289–6311.
[26] N.P. Cook, V. Torres, D. Jain, A.A. Marti, J. Am. Chem. Soc. 133 (2011) 11121–11123.
[27] A. Kumar, L. Moody, J.F. Olaivar, N.A. Lewis, R.L. Khade, A.A. Holder, Y. Zhang, V. Rangachari, ACS Chem. Neurosci. 1 (2010) 691–701.

[28] S.C. Lim, B.M. Paterson, M.T.F. Tavoletti, G.J. O'Keefe, R. Cappai, K.J. Barnham, V. L. Villemagne, P.S. Donnelly, Chem. Commun. 46 (2010) 5437–5439.
[29] M. Sagnou, D. Benaki, C. Triantis, T. Tsotakos, V. Psycharis, C.P. Raptopoulou, I. Pirmettis, M. Papadopoulos, M. Pelecanou, Inorg. Chem. 50 (2011) 1295–1303.
[30] M. Sagnou, S. Tzanopoulou, C.P. Raptopoulou, V. Psycharis, H. Braband, R. Alberto, I.C. Pirmettis, M. Papadopoulos, M. Pelecanou, Eur. J. Inorg. Chem. (2012) 4279–4286.
[31] J.J. Braymer, J.-S. Choi, A.S. DeToma, C. Wang, K. Nam, J.W. Kampf, A. Ramamoorthy, M.H. Lim, Inorg. Chem. 50 (2011) 10724–10734.
[32] H.F. Kung, S.R. Choi, W. Qu, W. Zhang, D. Skovronsky, J. Med. Chem. 53 (2010) 933–941.
[33] C. Rowe, U. Ackerman, W. Browne, R. Mulligan, K.L. Pike, G. O'Keefe, H. Tochon-Danguay, G. Chan, S.U. Berlangieri, G. Jones, K.L. Dickinson-Rowe, H.P. Kung, W. Zhang, M.P. Kung, D. Skovronsky, T. Dyrks, G. Hall, S. Krause, M. Friebe, L. Lehman, S. Lindemann, L.M. Dinkelborg, C.L. Masters, V. L. Villemagne, Lancet Neurol. 7 (2008) 129–135.
[34] V. Sathish, E. Babu, A. Ramdass, Z.Z. Lu, T.T. Chang, M. Velayudham, P. Thanasekaran, K.-L. Lu, W.S. Li, S. Rajagopal, RSC Adv. 3 (2013) 18557–18566.
[35] V. Sathish, A. Ramdass, Z.Z. Lu, M. Velayudham, P. Thanasekaran, K.-L. Lu, S. Rajagopal, J. Phys. Chem. B 117 (2013) 14358–14366.
[36] K.W.W. Lo, K.H.K. Tsang, W.K. Hiu, N. Zhu, Inorg. Chem. 44 (2005) 6100–6110.
[37] T.K. Dam, R. Roy, D. Page, C.F. Brewer, Biochemistry 41 (2002) 1351–1358.
[38] M.L. Verdonk, J.C. Cole, M.J. Hartshorn, C.W. Murray, R.D. Taylor, Proteins 52 (2003) 609–623.
[39] E.F. Pettersen, T.D. Goddard, C.C. Huang, G.S Couch, D.M. Greenblatt, E.C. Meng, T.E. Ferrin, J. Comput. Chem. 25 (2004) 1605–1612.
[40] X.-B. Yin, Y-Y. Xin, Y. Zhao, Anal. Chem. 81 (2009) 9299–9305.
[41] S. Shi, J. Zhao, X. Geng, T. Yao, H. Huang, T. Liu, L. Zheng, Z. Li, D. Yang, L. Ji, Dalton Trans. 39 (2010) 2490–2493.
[42] A.E. Friedman, J.C. Chambron, J.P. Sauvage, N.J. Turro, J.K. Barton, J. Am. Chem. Soc. 112 (1990) 4960–4962.
[43] G.R. Morais, A. Paulo, I. Santos, Eur. J. Org. Chem. (2012) 1279–1293.
[44] E.D. Agdeppa, V. Kepe, J. Liu, G.W. Small, S.-C. Huang, A. Petric, N. Satyamurthy, J.R. Barrio, Mol. Imaging Biol. 4 (2003) 404–417.
[45] J.L. Hickey, S.C. Lim, D.J. Hayne, B.M. Paterson, J.M. White, V.L. Villemagne, P. Roselt, D. Binns, C. Cullinane, C.M. Jeffery, R.I. Price, K.J. Barnhan, P. S. Donnelly, J. Am. Chem. Soc. 135 (2013) 16120–16132.
[46] M.J. Kaminski, C.R. MacKenzie, M.J. Mooibroek, T.E.S. Dahms, T. Hirama, A. N. Houghton, P.B. Chapman, S.V. Evans, J. Biol. Chem. 274 (1999) 5597–5604.
[47] A.I. Sulatskaya, I.M. Kuznetsova, K.K. Turoverov, J. Phys. Chem. B 116 (2012) 2538–2544.
[48] A.I. Sulatskaya, I.M. Kuznetsova, K.K. Turoverov, J. Phys. Chem. B 115 (2011) 11519–11524.
[49] A. Quest, I. Doudevski, H. Lin, R. Azimova, D. Ng, B. Frangione, B. Kagan, J. Ghiso, R. Lal, Proc. Natl. Acad. Sci. USA 102 (2005) 10427–10432.
[50] D.H.J. Bunka, B.J. Mantle, I.J. Morten, G.A. Tennent, S.E. Radford, P.G. Stockley, J. Biol. Chem. 282 (2007) 34500–34509.
[51] C. Ionescu-Zanetti, R. Khurana, J.R. Gillespie, J.S. Petrick, L.C. Trabachino, L. J. Minert, S.A. Carter, A.L. Fink, Proc. Natl. Acad. Sci. USA 96 (1999) 13175–13179.
[52] J. Bieschke, Q. Zhang, E.T. Powers, R.A. Lerner, J.W. Kelly, Biochemistry 44 (2005) 4977–4983.
[53] Y. Fezoui, D.M. Hartley, J.D. Harper, R. Khurana, D.M. Walsh, M.M. Condron, D. J. Selkoe, P.T. Lansbury Jr., A.L. Fink, D.B. Teplow, Amyloid 7 (2000) 166–178.
[54] S.A. Waldauer, S. Hassan, B. Paoli, P.M. Donaldson, R. Pfister, P. Hamm, A. Caflisch, R. Pellarin, J. Phys. Chem. B 116 (2012) 8961–8973.
[55] V. Gomathi Sankareswari, D. Vinod, A. Mahalakshmi, M. Alamelu, G. Kumaresan, R. Ramaraj, S. Rajagopal, Dalton. Trans. 43 (2014) 3260–3272.
[56] E. Babu, S. Singaravadivel, P. Manojkumar, S. Krishnasamy, G. Gnana kumar, S. Rajagopal, Anal. Bioanal. Chem. 405 (2013) 6891–6895.