COMMUNICATION www.rsc.org/chemcomm | ChemComm

A DNA-templated catalyst: the preparation of metal-DNA nanohybrids and their application in organic reactions†

Ye Wang, Guanghui Ouyang, Jintang Zhang and Zhiyong Wang*

Received 17th July 2010, Accepted 6th September 2010
DOI: 10.1039/c0cc02632h

Different kinds of metal-DNA nanohybrids are synthesized from cheap natural DNA on a large scale. These air-stable M-DNA nanohybrids maintain the advantages of both DNA and the metal nanoparticles, which exhibit reversible solubility and high catalytic activities. Moreover, the M-DNA nanohybrids could be easily reused for several cycles.

Recently, heterogenous catalysts of nanoscale particles immobilized on various templates caught wide interests.[1] Many inorganic solids and polymers have been used as templates, showing great impact on the physical and chemical character of nano-catalysts.[2] As an important biopolymer with many unique features, DNA has been well demonstrated to be a suitable template for many metal and metal oxide nanoparticles (NPs).[3] Considering the sophisticated geometric structures of DNA-templated NPs and potential functions of DNA,[4,5] we attempted to use DNA-templated metal NPs as heterogeneous catalysts in organic reactions. On the other hand, we attempted to make use of DNA chirality[6] since the metal NPs bind to the base pairs of DNA. However, few reports involved DNA-templated metal NPs in organic reactions perhaps due to the complicated technologies and small amount of production of DNA-templated nanomaterials. Meanwhile, natural DNA extracted from living creatures has attracted much attention since it is quite plentiful and cheap in the real world.[7] Herein, by using natural fish sperm DNA as a new kind of template, we synthesized different metal-DNA (M-DNA) nanohybrids (M = Pd, Au, Ag and Pt) on a large scale, and employed them as the catalysts for organic reactions. The reactions proceeded efficiently and the catalysts could be reused for several times. To the best of our knowledge, this is the first example of the DNA-templated metal nanomaterials acting as catalysts for organic reactions.

In all kinds of DNA-templated metal NPs, the preparation of palladium-DNA has been well researched.[3a,4b,c] In our experiments, K_2PdCl_4 and fish sperm DNA were chosen as the starting materials to synthesize nanohybrid in Tris buffer (Tris(hydroxymethyl)-aminomethane, 10 mM, pH = 7.4). As shown in the ESI†, the dosage of DNA template and the selection of suitable reductants had a great influence on the fabrication of nanohybrid. After optimization, sodium borohydride was employed to reduce Pd^{2+} in the presence of DNA and a dense homogeneous black solution was obtained. No precipitation or aggregation were observed even after centrifugation with 10 000 rpm. This indicated the material was highly dispersed in water with the aid of the DNA template. Moreover, the solution was air-stable, which could be placed in air for several days remaining homogeneous. The amount of the preparation could be scaled up to hundreds of millilitres easily at a time.

The as-synthesized solution (inset of Fig. 1A) was characterized in detail. TEM image and XRD pattern (Fig. 1A and ESI†) showed that this homogeneous solution contained nano scale Pd^0 particles with an average diameter of about 7-8 nm. Then, the UV-Vis spectra of pure DNA, Pd^{2+}-DNA and Pd-DNA (Fig. 2) clearly indicated the interactions between Pd NPs and DNA and thus verified the formation of new hybrid material. IR and ^{31}P NMR of Pd-DNA were further investigated to enhance this conclusion.[8]

After successful synthesis of Pd-DNA, taking the same method, $KAuCl_4$, $AgNO_3$ and K_2PtCl_6 were used to replace K_2PdCl_4 respectively and in all cases homogeneous solutions (inset of Fig. 1B–D) were synthesized smoothly. Similar measurement of TEM, XRD and UV-Vis (Fig. 1B–D and ESI†) indicated that the corresponding M-DNA (M = Au, Ag and Pt) nanohybrids were also obtained.

The as-prepared M-DNA nanohybrids maintain the characteristics of both the DNA molecules and the metal NPs. Firstly, in accordance with the pure DNA, the M-DNA nanohybrids could be precipitated from aqueous media by the addition of alcohol, and redispersed smoothly in water as shown in Fig. 3. After this redispersion, these M-DNA were purified, and the accurate metal concentrations

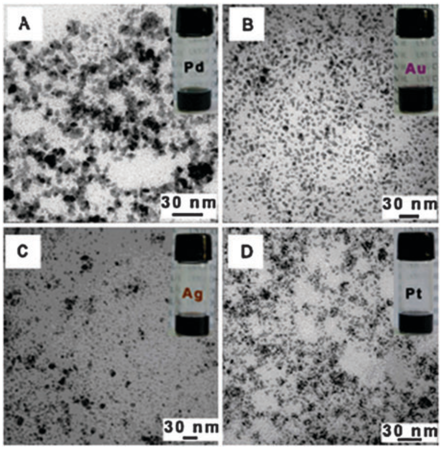


Fig. 1 TEM images of different M-DNA nanohybrids: (A) Pd-DNA; (B) Au-DNA; (C) Ag-DNA; (D) Pt-DNA.

Hefei National Laboratory for Physical Sciences at Microscale, CAS Key Laboratory of Soft Matter Chemistry and Department of Chemistry, University of Science and Technology of China, Hefei, 230026, P. R. China. E-mail: zwang3@ustc.edu.cn; Fax: (+86) 551-360-3185

† Electronic supplementary information (ESI) available: Experimental details, characterization of M-DNA before and after recycling, reaction optimization and characterization of **2a–2j**. See DOI: 10.1039/c0cc02632h/

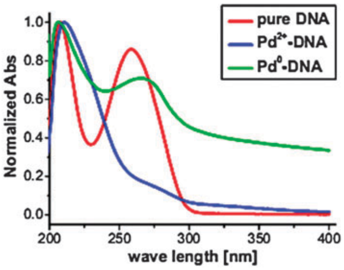


Fig. 2 Normalized UV-Vis spectra of different solution: red line: DNA in Tris; blue line: Pd^{2+}-DNA in Tris; green line: Pd-DNA in Tris.

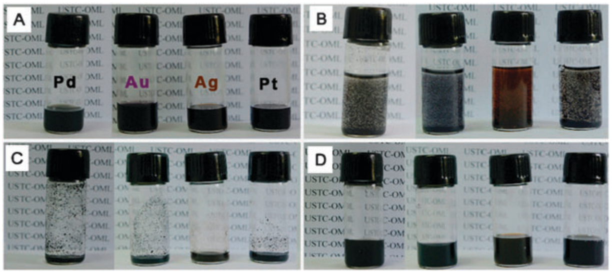
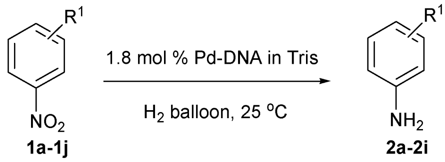


Fig. 3 (A) As-synthesized M-DNA nanohybrid solution. (B) After addition of 2–3 times volume of EtOH and placement still for 0.5 h. (C) Precipitate after pouring out the colorless solution. (D) Homogeneous solution after addition of Tris buffer back to the precipitate.

Table 1 Reduction of aromatic nitro compounds catalyzed by Pd-DNA[a]



Entry	R^1	Time/h	EtOH	Product	Yield (%)[b]
1	1-H	4	—	**2a**	95
2	2-Me	8	—	**2b**	80
3	4-Me	8	—	**2c**	89
4	4-OMe	6	2 ml	**2d**	97
5	4-COOH	8	—	**2e**	97
6	4-COOEt	8	2 ml	**2f**	99
7	4-OTs	8	2 ml	**2g**	80
8[c]	3-NO_2	6	—	**2h**	94
9	3-NH_2	8	2 ml	**2h**	83
10	2-CHO	6	2 ml	**2i**	83

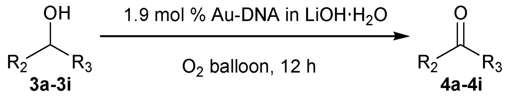
[a] Reaction conditions: **1** (1 mmol), Pd-DNA in Tris (4 ml, 1.8 mol%), H_2 balloon, 25 °C. [b] Isolated yield. [c] **1h** (0.5 mmol) was used.

of the M-DNA nanohybrids (M = Pd, Au, Ag and Pt) could be determined by direct ICP-OES measurement. The concentration of all the starting metal ions was 5 mM. After purification, ICP-OES indicated that concentrations of different elements were turned out to be 4.6 mM for Pd, 4.8 mM for Au, 3.9 mM for Ag and 3.4 mM for Pt respectively. Moreover, different buffers of different pH such as MES (4-morpholineethanesulfonic acid hydrate, 10 mM, pH = 5.5) and $NaHCO_3$–Na_2CO_3 (pH = 10.5) could also redissolve the M-DNA nanohybrids well besides Tris. Surprisingly, even in the solutions of strong bases like NaOH and *t*BuOK, these M-DNA could also dissolve smoothly and remain homogeneously, which proved the high stability of these M-DNA nanohybrids.

Subsequently, the M-DNA nanohybrids were used as efficient catalysts for organic reactions. Firstly, the hydrogenation of nitrophenyl compounds to aniline derivatives under H_2 was investigated.[9] The hydrogenation of nitrobenzene was studied as a model reaction. After optimization,[8] Pd-DNA was found to be the best catalyst for the reduction. Under the same conditions Pt-DNA was less reactive while Au-DNA and Ag-DNA showed little catalytic activity for this hydrogenation. 1.8 mol% of redissolved Pd-DNA in Tris was used to catalyze the hydrogenation of nitrobenzene into aniline, affording the corresponding product with an isolated yield of 95% (Table 1, entry 1). Then different reaction substrates were employed. As shown in Table 1, various aromatic nitro compounds, bearing electron-deficient, electron-rich and neutral groups, can be reduced into aniline derivatives smoothly with the catalyst of Pd-DNA nanohybrid at 25 °C (Table 1, entries 2–4, 8). Moreover, substrates with sensitive functional groups such as aldehyde, carboxylic acid and ester also survived the reaction (Table 1, entries 5–7, 10). It was noted that the solubility of the reaction substrates affected the reaction remarkably. The water-insoluble substrates were hardly reduced even under vigorous stirring (Table 1, entries 4, 6, 7, 9, 10). To solve this problem, addition of organic solvents were tested. It was found adding 1/2 volume of EtOH could maintain the homogeneous Pd-DNA solutions and enhance the reaction yields. The addition of other solvents such as ethyl acetate, THF, ether and acetone could generally destroy the homogeneous Pd-DNA solutions during the reduction and result in the formation of Pd black. The catalytic reactivity of this Pd-DNA nanohybrid was also compared with other hydrogenation catalysts, as shown in Table ESI-2†.[8] Only Pd-DNA catalyst led to both high chemoselectivity and high conversion, which indicated the great efficiency of Pd-DNA nanohybrid as catalyst.

Secondly, the M-DNA nanohybrids were employed as catalysts for oxidation reactions.[10] The aerobic oxidation of 1-phenylethynol to acetophenone was chosen as a model reaction. Experimental results indicated that Au-DNA exhibited the highest catalytic reactivity.[8] After optimization of bases,[8] the oxidation proceeded well under quite mild conditions. 1.9 mol% of Au-DNA nanohybrid, which was purified and redissolved in 2 equivalents of $LiOH{\cdot}H_2O$ solution, was used as the catalyst with oxygen balloon at 25 °C for 12 h. Under these conditions, the substrate scope was investigated. 1-phenylethynol completely converted to acetophenone (Table 2, entry 1). Electronic effect had little influence on this oxidation (Table 2, entries 2–3). Substrate with steric effect was also oxidized quantitatively at 50 °C (Table 2, entry 5). When the phenyl ring was replaced with pyridine, the reaction yield was decreased which may be due to the strong coordination between N and Au NPs (Table 2, entry 6). For solid substrate with poor solubility in water, the yield was lower (Table 2, entry 4) and even EtOH was needed (Table 2, entry 7). Aliphatic alcohol was oxidized to afford the corresponding ketone smoothly (Table 2, entry 8). Cyclohexanol can be a substrate in this oxidation in spite of a moderate yield (Table 2, entry 9). Notably, the Au-DNA nanohybrid was stable and kept homogeneous solution before and after the reaction.

Table 2 Oxidation of alcohols to ketones catalyzed by Au-DNA[a]



Entry	Substrate R^2	 R^3	Yield (%)[b]
1	Ph	Me	> 99
2	4-Me-Ph	Me	> 99
3	4-F-Ph	Me	> 99
4	4-NO_2-Ph	Me	87
5	2-Me-Ph	Me	> 99[c]
6	2-Py	Me	60[c]
7	Ph	Ph	82[c,d]
8	1,2,3,4-Tetrahydro-1-naphthol		> 99
9	Cyclohexanol		60

[a] Reaction conditions: **3** (0.5 mmol), Au-DNA (2 ml, 1.9 mol%) redissolved in 2 ml solution of 1 mmol LiOH·H_2O, O_2 balloon, 25 °C, 12 h. [b] Determined by GC-MS analysis with internal standard. [c] 50 °C. [d] 1 ml EtOH was added.

Combining the unique features of DNA and metal nanoparticles, M-DNA nanohybrids could act as reusable catalysts for organic reactions. In both reduction and oxidation, 2 volume of EtOH was added to the reaction mixture after the reaction and the catalysts were precipitated on the bottom while the products were dissolved in the solution. The catalyst can be easily recovered by a simple phase separation, redissolved in solvents and directly reused for the next round.

The hydrogenation of ethyl 4-nitrobenzoate was selected as an example. The results are listed in Table 3. At the fifth round, the reaction time was extended and the reaction yield was reduced to 80%. TEM image and UV-Vis spectra of the Pd-DNA[8] indicated that Pd-DNA was partially destroyed and Pd^0 was aggregated and gradually leached into Pd^{2+} to bind with the DNA, resulting in the decrease of catalytic activity. Better results were gained when employing the oxidation of 1-phenylethynol to test the reusability of Au-DNA as shown in Table 4. Au-DNA nanohybrid could be reused without significant loss of activity up to 7 times with a mild heating at the 5th–7th runs. Similar aggregation of Au NPs was also detected after recycling.[8]

In summary, different M-DNA nanohybrids (M = Pd, Au, Ag and Pt) were prepared from a cheap natural DNA under mild conditions. Detailed characterizations indicated that there was interaction between metal NPs and DNA which stabilized the metal NPs. The as-synthesized M-DNA revealed both the unique features of DNA and metal nanoparticles. Dramatic solubility of M-DNA nanohybrids like pure DNA facilitated the purification and phase separation. Most of these M-DNA nanohybrids were efficient catalysts in different organic reactions in aqueous media. The M-DNA nanohybrids can be well reused with combined unique features of DNA and metal nanoparticles. The preparation of other M-DNA nanohybrids and their applications including asymmetric catalysis are in progress in our laboratory.

Table 3 Recycling of Pd-DNA for reduction of ethyl 4-nitrobenzoate[a]

$$\mathbf{1f} \xrightarrow[\text{H}_2\text{ balloon, 25 }^{o}\text{C}]{\text{Pd-DNA in Tris}} \mathbf{2f}$$

Run	1	2	3	4	5
Time/h	8	9.5	11	13	20
Yield (%)[b]	99	99	96	90	80

[a] Reaction conditions: **1f** (1 mmol), Pd-DNA (initially 1.8 mol%) in 4 ml Tris, EtOH (2 ml), H_2 balloon, 25 °C. [b] Isolated yield.

Table 4 Recycling of Au-DNA for oxidation of 1-phenylethynol[a]

$$\mathbf{3a} \xrightarrow[\text{O}_2\text{ balloon, 12h}]{\text{Au-DNA in LiOH}\cdot\text{H}_2\text{O}} \mathbf{4a}$$

Run	1	2	3	4	5	6	7
T/°C	25	25	25	25	50	50	50
Yield (%)[b]	> 99	> 99	93	89	> 99	95	90

[a] Reaction conditions: **3a** (0.5 mmol), Au-DNA (initially 1.9 mol%) redissolved in 2 ml solution of 1 mmol of LiOH·H_2O, O_2 balloon, 12 h. [b] Determined by GC-MS analysis with internal standard.

We are grateful to the National Natural Science Foundation of China (20628202, 90813008, 20972144, 20772118 and 20932002) and the Graduate Innovation Fund of USTC.

Notes and references

1 For recent reviews, see: (*a*) A. Corma and H. Garcia, *Chem. Soc. Rev.*, 2008, **37**, 2096; (*b*) Juan M. Campelo, D. Luna, R. Luque, José M. Marinas and Antonio A. Romero, *ChemSusChem*, 2009, **2**, 18; (*c*) J. M. Fraile, J. I. Garcia, C. I. Herrerias, J. A. Mayoral and E. Pires, *Chem. Soc. Rev.*, 2009, **38**, 695; (*d*) J. Lu and P. H. Toy, *Chem. Rev.*, 2009, **109**, 815; (*e*) S. J. Wang, Z. Y. Wang and Z. G. Zha, *Dalton Trans.*, 2009, 9363; (*f*) R. J. White, R. Luque, V. L. Budarin, J. H. Clark and D. J. Macquarrie, *Chem. Soc. Rev.*, 2009, **38**, 481.

2 For examples see: (*a*) P. D. Stevens, G. F. Li, J. D. Fan, M. Yen and Y. Gao, *Chem. Commun.*, 2005, 4435; (*b*) A. Corma and P. Serna, *Science*, 2006, **313**, 332; (*c*) David J. Mihalcik and W. Lin, *Angew. Chem., Int. Ed.*, 2008, **47**, 6229; (*d*) S. Benyahya, F. Monnier, M. W. C. Man, C. Bied, F. Ouazzani and M. Taillefer, *Green Chem.*, 2009, **11**, 1121; (*e*) S. Wang, X. He, L. Song and Z. Wang, *Synlett*, 2009, 447; (*f*) M.-J. Jin and D.-H. Lee, *Angew. Chem., Int. Ed.*, 2010, **49**, 1119; (*g*) C. A. Witham, W. Y. Huang, C. K. Tsung, J. N. Kuhn, G. A. Somorjai and F. D. Toste, *Nat. Chem.*, 2010, **2**, 36; (*h*) B. Z. Yuan, Y. Y. Pan, Y. W. Li, B. L. Yin and H. F. Jiang, *Angew. Chem., Int. Ed.*, 2010, **49**, 4054.

3 (*a*) J. Richter, R. Seidel, R. Kirsch, M. Mertig, W. Pompe, J. Plaschke and H. K. Schackert, *Adv. Mater.*, 2000, **12**, 507; (*b*) M. Mertig, L. C. Ciacchi, R. Seidel, W. Pompe and A. De Vita, *Nano Lett.*, 2002, **2**, 841; (*c*) W. U. Dittmer and F. C. Simmel, *Appl. Phys. Lett.*, 2004, **85**, 633; (*d*) J. M. Kinsella and A. Ivanisevic, *Langmuir*, 2007, **23**, 3886; (*e*) H. Wang, R. Yang, L. Yang and W. Tan, *ACS Nano*, 2009, **3**, 2451; (*f*) C. T. Wirges, J. Timper, M. Fischler, A. S. Sologubenko, J. Mayer, U. Simon and T. Carell, *Angew. Chem., Int. Ed.*, 2009, **48**, 219.

4 (*a*) K. Keren, R. S. Berman, E. Buchstab, U. Sivan and E. Braun, *Science*, 2003, **302**, 1380; (*b*) Y. Hatakeyama, M. Umetsu, S. Ohara, F. Kawadai, S. Takami, T. Naka and T. Adschiri, *Adv. Mater.*, 2008, **20**, 1122; (*c*) K. Nguyen, M. Monteverde, A. Filoramo, L. Goux-Capes, S. Lyonnais, P. Jegou, P. Viel, M. Goffman and J. P. Bourgoin, *Adv. Mater.*, 2008, **20**, 1099.

5 H. A. Becerril and A. T. Woolley, *Chem. Soc. Rev.*, 2009, **38**, 329.

6 A. J. Boersma, R. P. Megens, B. L. Feringa and G. Roelfes, *Chem. Soc. Rev.*, 2010, **39**, 2083.

7 X. D. Liu, H. Y. Diao and N. Nishi, *Chem. Soc. Rev.*, 2008, **37**, 2745.

8 See the ESI† for details.

9 For examples of hydrogenation catalyzed by nano-catalysts, see ref. 1*f*.

10 For examples of oxidation catalyzed by nano-catalysts, see: H. Miyamura, R. Matsubara, Y. Miyazaki and S. Kobayashi, *Angew. Chem., Int. Ed.*, 2007, **46**, 4151. and ref. 1*a*.