

Synthesis of Triple-ringed [14]Arene via Dynamic Covalent Chemistry Mechanism in Condensation Reaction of Phenols with *m*-Benzenedicarbaldehyde

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(Received March 6, 2012; CL-120192; E-mail: kudoh@kansai-u.ac.jp)

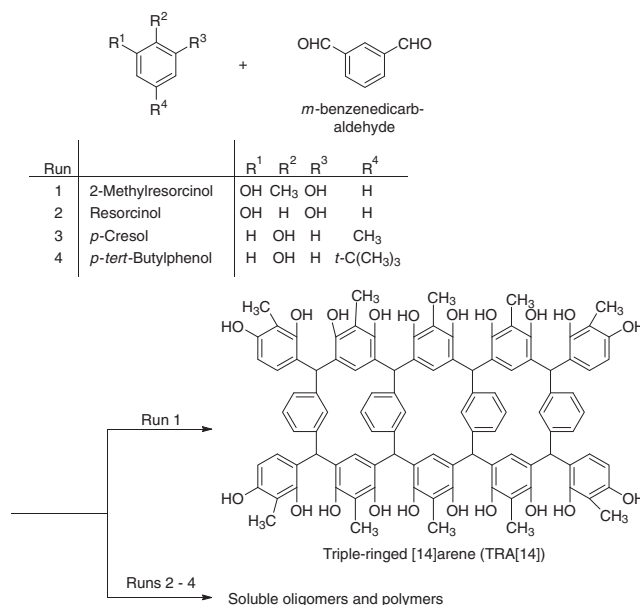
Condensation reaction of 2-methylresorcinol with *m*-benzenedicarbaldehyde in the presence of HCl as a catalyst in *n*-propanol at 90 °C for 48 h proceeded via a dynamic covalent chemistry (DCC) mechanism to afford a triple-ringed [14]arene in 52% yield.

Dynamic covalent chemistry (DCC), which involves reversible covalent bond formation, is a powerful tool for the construction of covalently linked nanostructures.¹ DCC selectively provides the most thermodynamically stable molecules under appropriate reaction conditions and can be used to construct three-dimensional cage structures in a one-pot procedure. Imine bond formation,^{2,3} boronic acid condensation,^{4,5} alkoxy amine exchange,⁶ ester bond exchange,⁷ acetal bond exchange,⁸ and disulfide bond exchange⁹ have been utilized to synthesize unique, covalently linked nanostructures via the DCC mechanism. Zhang and his co-workers employed the DCC approach to selectively obtain a three-dimensional cage structure by means of imine bond formation reaction of triamine with dialdehyde using Sc(OTf)₃ as a catalyst in chloroform at room temperature. Interestingly, this cage showed highly selective adsorption of CO₂ over N₂ under standard temperature and pressure (STP, 20 °C, 1 bar).¹⁰

Recently, we have succeeded in the synthesis of a ladder-type cyclic oligomer, noria (water wheel in Latin), through DCC-based condensation reaction of resorcinol and 1,5-pentanedial, using a feed ratio of resorcinol:1,5-pentanedial = 4:1 in the presence of HCl as a catalyst in ethanol at 80 °C for 48 h.¹¹ Similar condensation reactions of 1,5-pentanedial with other phenols, 2-methylresorcinol, pyrogallol, and 3-alkoxyphenol, selectively afforded corresponding noria-like three-dimensional cage structures.^{12,13} Thus, we considered that DCC-type condensation reactions of phenols and dialdehydes in other combinations, under appropriate reaction conditions, might also generate other unique nanostructures. In this paper, we present the results of a detailed examination of the DCC-type condensation reactions of *m*-benzenedicarbaldehyde with resorcinol, 2-methylresorcinol, *p*-cresol, and *p*-*tert*-butylphenol.

These condensation reactions were carried out in *n*-propanol at 90 °C in the presence of HCl as a catalyst (Scheme 1). The phenols and *m*-benzenedicarbaldehyde have two and four condensation points, respectively, i.e., this system is an A₂ + B₄ type condensation reaction. Oligomers and polymers were obtained in all cases, and no gel product was formed. Figure 1 depicts the size exclusion chromatography (SEC) profiles of these oligomers and polymers. The results are summarized in Table 1.

In the case of 2-methylresorcinol, the SEC profile showed a unimodal peak and the value of molecular dispersity ratio



Scheme 1. Condensation reaction of various phenols with *m*-benzenedicarbaldehyde.

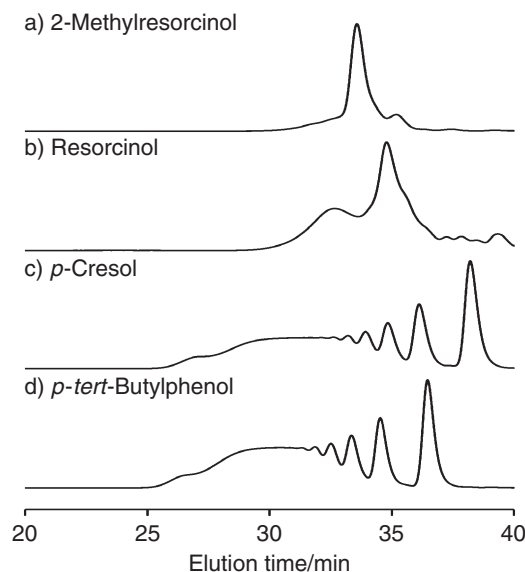
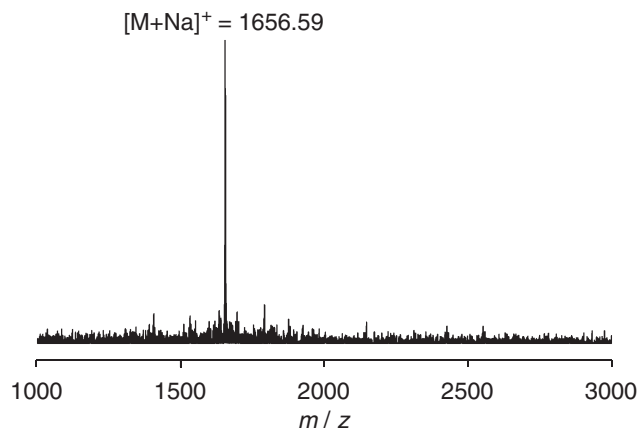


Figure 1. SEC profiles of the condensation reaction of various phenols with *m*-benzenedicarbaldehyde.

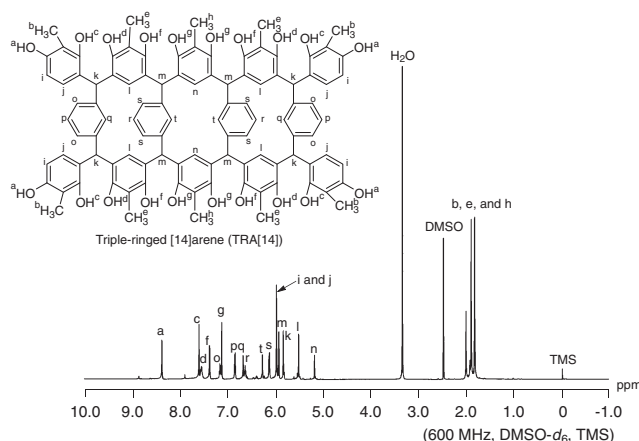
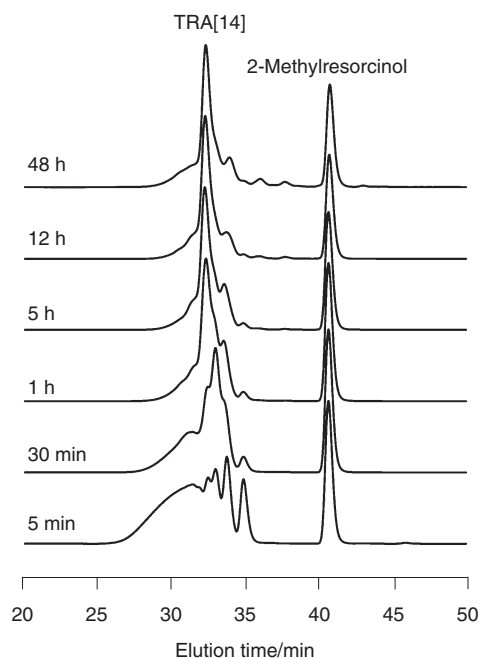
Table 1. Condensation reaction of various phenols with *m*-benzenedicarbaldehyde^a

| Run | Phenols | M_n (M_w/M_n) | |
|-----|-------------------------------------|---------------------|------------|
| 1 | 2-Methylresorcinol | 1750 (1.02) | Unimodal |
| 2 | Resorcinol | 1500 (1.20) | Multimodal |
| 3 | <i>p</i> -Cresol | 990 (2.75) | Multimodal |
| 4 | <i>p</i> - <i>tert</i> -Butylphenol | 1730 (3.73) | Multimodal |

^aThese condensation reactions of various phenols with *m*-benzenedicarbaldehyde were carried out using HCl as a catalyst in *n*-propanol as a solvent at 90 °C for 48 h.

**Figure 2.** MALDI-TOF mass spectrum of triple-ringed [14]arene (TRA[14]).

(M_w/M_n) was very narrow: 1.02 (Figure 1a). The soluble oligomers obtained in the case of resorcinol, *p*-cresol, and *p*-*tert*-butylphenol showed multimodal peaks with $M_n = 1500$, 990, and 1730, and $M_w/M_n = 1.20$, 2.75, and 3.73, respectively (Figures 1b, 1c, and 1d). It seems that these condensation reactions proceeded according to a DCC mechanism, affording soluble oligomers. However, it was difficult to separate the products and confirm their structures. In the case of 2-methylresorcinol, oligomer was obtained by pouring the reaction mixture into a large amount of *n*-propanol. Its structure was examined by ¹H NMR, ¹³C NMR, and MALDI-TOF mass spectrometry, besides elementary analysis. MALDI-TOF mass spectrum of this product doped with Na⁺ ion showed a parent ion signal at m/z 1656.59 (Figure 2), which corresponds to the mass of a cyclic oligomer formed by the condensation reaction of ten equivalents of 2-methylresorcinol with four equivalents of *m*-benzenedicarbaldehyde. Furthermore, the ¹H NMR spectrum showed five singlet signals at 8.41, 7.63, 7.58, 7.41, and 7.15 ppm assignable to hydroxy protons, nine signals at 7.19, 6.88, 6.70, 6.66, 6.30, 6.16, 6.00, 5.54, and 5.21 ppm assignable to aromatic protons, two singlet signals at 5.95 and 5.86 ppm assignable to methine protons, and three singlet signals at 2.20, 1.92, and 1.84 ppm assignable to methyl protons, respectively (Figure 3). Its ¹³C NMR spectrum (SI; Figure S2¹⁴) and elemental analysis data also supported the corresponding structures.¹⁴ These results strongly indicate that the condensation reaction of 2-methylresorcinol with *m*-benzenedicarbaldehyde afforded a unique cyclic oligomer with a symmetric three-ringed structure having 20 pendant hydroxy groups and 10 methyl

**Figure 3.** ¹H NMR spectrum of triple-ringed [14]arene (TRA[14]).**Figure 4.** Time-course of SEC profiles during the condensation reaction of 2-methylresorcinol with *m*-benzenedicarbaldehyde.

groups, as shown in Scheme 1. We named this product triple-ringed [14]arene (TRA[14]) (yield: 52%).

Next, we examined the effect of reaction time on the condensation reaction leading to TRA[14] by means of SEC. Figure 4 shows the time course of SEC profiles of the products formed by condensation reaction of 2-methylresorcinol with *m*-benzenedicarbaldehyde. Initially, polymer and oligomer were produced, and then these products were converted to TRA[14] with increasing reaction time. This result confirms that the reaction proceeded according to a DCC mechanism to give the most thermodynamically stable compound, TRA[14], selectively.

We have already reported that noria derivatives with pendant acid-labile groups such as *tert*-butoxycarbonyl,¹⁵ *tert*-butyl ester,¹⁶ cyclohexyl acetal,¹⁷ and adamantyl ester groups,¹⁸

and polymerizable groups such as oxetanyl,¹⁹ vinyl ether, and methacryloyl groups²⁰ are candidates for high-performance photofunctional materials, such as photoresists and UV-curing materials. Therefore, the solubility and thermal stability of TRA[14] were examined. TRA[14] was soluble in common organic solvents such as dimethyl sulfoxide, *N,N*-dimethylformamide, *N,N*-dimethylacetamide, methanol, acetone, and tetrahydrofuran. The temperature of 5 wt % loss ($T_d^{5\%}$) of TRA[14], measured by thermogravimetric analysis, was 340 °C. Thus, TRA[14] has better solubility and higher thermal stability than noria. Therefore, TRA[14] derivatives appear to be promising candidates for application as photofunctional materials.

In summary, we examined the condensation reaction of several phenols (resorcinol, 2-methylresorcinol, *p*-cresol, and *p*-*tert*-butylphenol) as A₂-type monomers with *m*-benzenedicarbaldehyde as a B₄-type monomer in *n*-propanol as a solvent using HCl as a catalyst at 90 °C for 48 h. In the case of the combination of 2-methylresorcinol and *m*-benzenedicarbaldehyde, the reaction proceeded according to a DCC mechanism, selectively affording an oligomer. Its structure was investigated by ¹H NMR, ¹³C NMR, and MALDI-TOF mass spectrometry, besides elementary analysis, and it was shown to be a triple-ringed [14]arene (TRA[14]). TRA[14] showed good solubility and high thermal stability, and its derivatives with pendant photoreactive groups are expected to be promising candidates as novel photoresists or UV-curing materials.

This paper is dedicated to the heartfelt memory of the late Professor Tadatomi Nishikubo of Kanagawa University.

References and Notes

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