# Calixarene-polymers via Simple Polymerization of *t*-Butylcalix[8]arenes (A$_8$-type Monomer) with Hexamethylene Diisocyanate (B$_2$-type Monomer); Molecular Bunch of Grapes (Botryosin)

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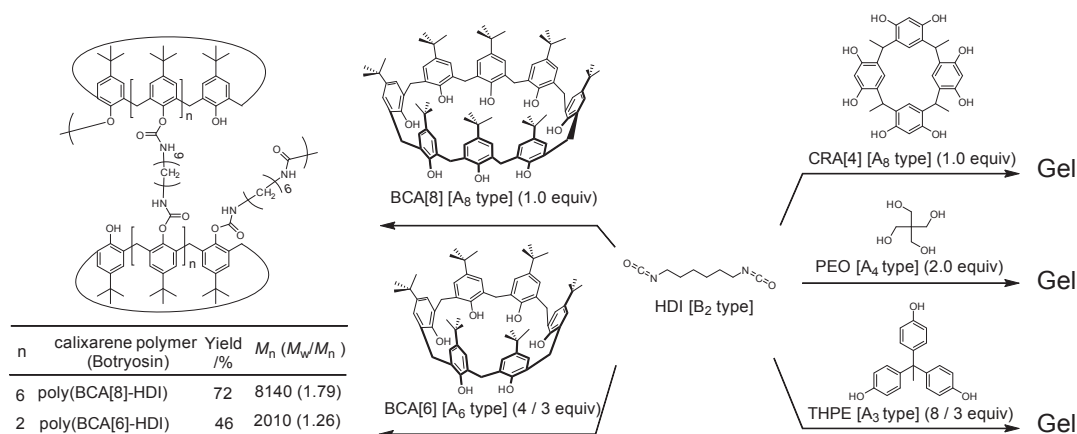(E-mail: kudoh@kansai-u.ac.jp, hayashi@echem.titech.ac.jp)

Reaction of *t*-butylcalix[8]arene (BCA[8]) as an A$_8$-type monomer with hexamethylene diisocyanate as a B$_2$-type monomer was examined to afford only soluble polymers in high yields. Analysis by $^1$H NMR, IR, MALDI-TOF mass spectroscopy, and AFM indicated that the synthesized polymers consist of nanoscale-gel-shaped structures that contain fixed holes and cavities. We designated this class of polymers as botryosin, after the Greek word botrys, meaning a bunch of grapes. Examination of host–guest chemistry of the synthesized polymers revealed complexation with alkali metal ions.

Three-dimensional macrocyclic compounds with fixed cavities that can selectively internalize various materials are called molecular cups,[1] molecular containers,[2] molecular baskets,[3] molecular cages,[4] and molecular capsules.[5] Their syntheses and properties have been reported by many researchers, and these compounds have potential value in a wide range of applications. However, their practical application is restricted by synthetic limitations. In a pioneering work on three-dimensional macrocycles, spherand, and cavitand were synthesized from calixarenes (CAs) in multistep reactions.[6] CAs are generally cone-shaped and can accommodate organic compounds or metal ions in their fixed holes.[7] Polymers bearing CA moieties in the main or side chains (CA-polymers) have also been synthesized and have potential applications as chemical sensors, selective membranes, and catalysts, as well as in microelectronic devices.[8]

Herein, we present an A$_8$ + B$_2$-type polymerization involving reaction of *t*-butylcalix[8]arene (BCA[8]) as an A$_8$-type

monomer with hexamethylene diisocyanate (HDI) as a B$_2$-type monomer to give soluble polymers containing BCA[8] structures in the main chain in high yields.

Reaction of BCA[8] (1.29 g, 1.0 mmol) and HDI (0.673 g, 4.0 mmol) was performed in the presence of NEt$_3$ (0.81 g, 8.0 mmol) in 1-methyl-2-pyrrolidone (NMP) (8.0 mL) at 25 °C for 12 h (Scheme 1). The reaction proceeded homogeneously. The reaction mixture was poured into a large amount of 1 M hydrochloric acid; the precipitated product was washed with water and methanol several times, and dried in vacuo at 60 °C for 12 h. The product (1.413 g) was soluble in common organic solvents such as dimethylformamide (DMF), dimethyl sulfoxide (DMSO), tetrahydrofuran (THF), chloroform (CHCl$_3$), and dichloromethane (CH$_2$Cl$_2$). Size exclusion chromatography (SEC) profiles showed multimodal peaks, and the number-average molecular weight ($M_n$) and molecular weight dispersity ratio ($M_w/M_n$) were 8140 and 1.79, respectively (Supporting Information, SI; Figure S1). The $^1$H NMR spectrum showed that the product contained aromatic, methylene, and –NH– protons (SI; Figure S2). The IR spectrum also indicated the presence of urethane and aromatic moieties (SI; Figure S3). The ratio of the units derived from BCA[8] and HDI was 1.0:3.6, calculated from the signal integral ratios in the $^1$H NMR spectrum. The degree ratio (DR) of addition reaction of BCA[8] and HDI was calculated to be 90% from the signal integral ratios for the remaining hydroxy protons and aromatic protons of BCA[8]. That is, soluble poly(BCA[8]-HDI) was synthesized in 72% yield. Generally, A$_n$ + B$_2$ ($n \geq 3$)-type polymerization gives gel products in high yields, but may also afford soluble



| n | calixarene polymer (Botryosin) | Yield /% | $M_n$ ($M_w/M_n$) |
|---|---|---|---|
| 6 | poly(BCA[8]-HDI) | 72 | 8140 (1.79) |
| 2 | poly(BCA[6]-HDI) | 46 | 2010 (1.26) |

**Scheme 1.** Reaction of HDI with BCA[8], BCA[6], CRA[4], PEO, and THPE.

**Table 1.** Polyaddition of BCA[8] and HDI[a]

| Run | Feed ratio BCA:DIH | DR/%[b] | Yield/%[c] | $M_n$ $(M_w/M_n)$[d] |
|-----|-----|-----|-----|-----|
| 1 | 1:8 | 99 | 84 | 3320 (1.87) |
| 2 | 1:6 | 99 | 63 | 3140 (1.46) |
| 3 | 1:4 | 90 | 72 | 8140 (1.79) |
| 4 | 1:1 | 30 | 75 | 2150 (1.23) |

[a]Reaction condition; at 25 °C in NMP for 24 h. [b]Calculated by $^1$H NMR. [c]Methanol-insoluble part. [d]Estimated by SEC (eluted of LiBr and CH$_3$COOH in DMF).
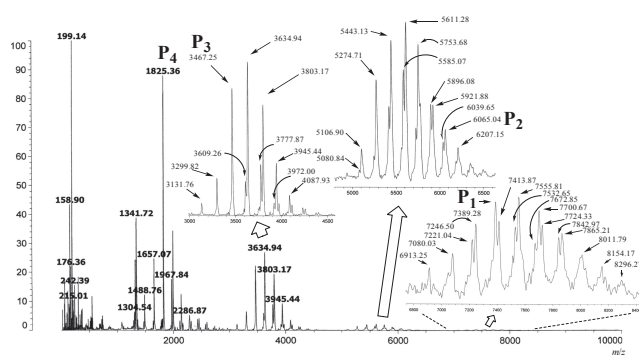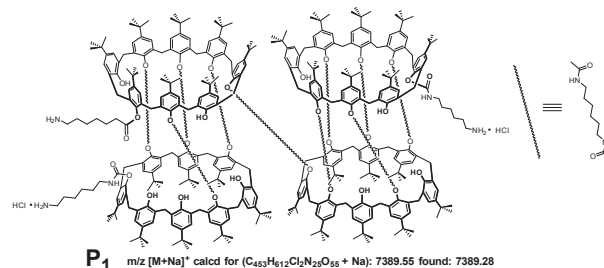


**Figure 1.** MALDI-TOF mass spectra of BCA[8]-based polymer ($M_n = 8140$, $M_w/M_n = 1.79$) (Run 3 in Table 1).



**P$_1$** m/z [M+Na]$^+$ calcd for (C$_{453}$H$_{612}$Cl$_2$N$_{25}$O$_{55}$ + Na): 7389.55 found: 7389.28

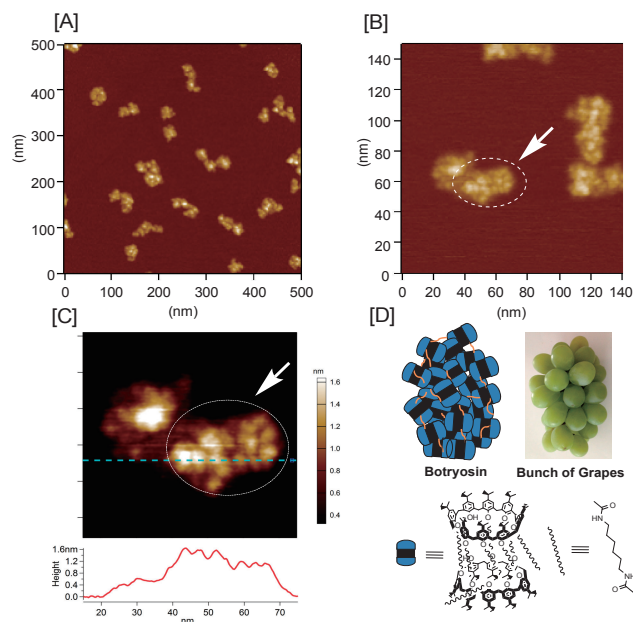**Scheme 2.** Plausible structures of **P$_1$**.



**Figure 2.** [A] AC-mode AFM topographic images of poly(BCA[8]-HDI) after spin-coating on an HOPG substrate (500 × 500 nm). [B] Locally enlarged picture (300 × 300 nm). [C] A close up observation image (60 × 60 nm) a cluster in the region indicated by the oval in [B] and its cross sectional view along the blue dotted line. [D] Estimated structure of tube-shaped polymer indicated by the oval in [C].

hyperbranched polymers if the monomer feed ratio and the reaction conditions are appropriately controlled.[9] However, in this case of A$_8$ + B$_2$-type polymerization, no gel product was obtained, and only soluble polymer was formed. The optimum conditions for this polyaddition reaction were examined using various feed ratios of BCA[8] and HDI. In all cases, no gel product was obtained and only soluble polymers. The reaction conditions and corresponding results are summarized in Table 1. Poly(BCA[8]-HDI) with high molecular weight was obtained even at an equivalent molar ratio of hydroxy and isocyanato groups.

Figure 1 depicts the MALDI-TOF mass spectra of this polymer (Run 3 in Table 1, $M_n = 8140$, $M_w/M_n = 1.79$). Mass difference patterns that corresponded to the molecular mass of HDI (M = 168.09) and BCA[8] (M = 1296.84) were seen. Furthermore, we also observed mass difference patterns with $m/z$ 178 and 142, corresponding to the mass of HDI derivatives containing –NH$_2$·HCl and –NH$_2$ moieties at the ends, respectively. **P$_1$** consists of 4 molecules of BCA[8], 10 molecules of HDI, 2 molecules of HDI derivatives with –NH$_2$·HCl at the end, and 1 molecule of HDI derivative with –NH$_2$ at the end (M = 7389.55). **P$_2$** consists of 3 molecules of BCA[8], 7 molecules of HDI, and 4 molecule of HDI derivative with –NH$_2$·HCl at the end, and 2 molecule of HDI derivative with –NH$_2$ at the end (M = 6064.73). **P$_3$** consists of 2 molecules of BCA[8], 6 molecules of HDI, and 1 molecule of HDI derivative with –NH$_2$·HCl at the end (M = 3467.13). **P$_4$** is consists of 1 molecule of BCA[8] and 3 molecules of HDI (M = 1824.11). These imply that poly(BCA[8]-HDI) has BCA[8] moieties in

the main chain. Although, the molecular weight is limited to ca. 10000, as determined from MALDI-TOF mass spectra, the weight-average molecular weight [$M_{w(MALLS)}$] determined by multi-angle light scattering (MALLS) was 105900. Considering that no gel product was formed, the plausible structure of **P$_1$** is shown in Scheme 2. (SI; Scheme S1). **P$_1$** might be main component of the high-molecular-weight polymer poly(BCA[8]-HDI).

Furthermore, a thin film of poly(BCA[8]-HDI) could be prepared on the silicon wafer by spin coating (see SI). Its structure was directly examined by atomic force microscopy (AFM), which revealed distinctive clusters of smaller structures (Figures 2A and 2B); each of these clusters appeared to be consistent with a molecule consisting of multiple, linked **P$_1$**-like capsules (Figures 2C and 2D).

The number of capsules comprising one cluster was 33 ± 8.3 ($n = 15$; counting was difficult because some capsules overlapped, and the values were affected by counting error originating from fuzziness of the boundaries between the

capsules). The averaged molecular weight of one capsule was calculated by $^1$H NMR to be ca. 3600, which is consistent with a degree of addition reaction of 90%, assuming that one capsule consists of two equivalents of BCA[8] ($M_w = 1297.86$) and 6 equivalents of HDI ($M_w = 168.20$). The molecular weight of 33 of the capsules observed on AFM was calculated to be 118900, which is close to the value of $M_{w(MALLS)} = 105900$. This means that the AFM image is consistent with the presence of poly(BCA[8]-HDI).

Furthermore, based on the height profile of the clusters, the minimum size of these moieties is 2 nm, in good agreement with the molecular capsule structure shown in Figure 2C. This suggests that **P₁**-like capsules are linked to form the connected nanoscale-gel-shaped polymer poly(BCA[8]-HDI), resembling a bunch of grapes in appearance, as shown in Figure 2D. We named it botryosin, which means a bunch of grapes in Greek. Thus, the reaction of BCA[8] (A₈-type monomer) and HDI (B₂-type monomer) proceeded to generate only a soluble polymer consisting of a cluster of nanoscale gels. Furthermore, the value of $M_{w(MALLS)}/M_{n(MALLS)}$ ($= 11.0$) was quite large. This means that poly(BCA[8]-HDI) had branched structures based on the unit of **P₁**-like capsules. It is noteworthy that these structures are not three-dimensionally crosslinked, because of which no insoluble product is formed.

We also examined the reactions of *t*-butylcalix[6]arene (BCA[6]) [A₆ type], calix[4]resorcinarene (CRA[4]) [A₈ type], pentaerythritol (PEO) [A₄ type], and 1,1,1-tris(4-hydroxyphenyl)ethane (THPE) [A₃ type] in the same way as described for the synthesis of poly(BCA[8]-HDI) (Scheme 1). For BCA[6], no gel product was obtained and only soluble poly(BCA[6]-HDI) with $M_n = 2010$ ($M_w/M_n = 1.26$) was obtained in 46% yield (see SI). On the other hand, only gel product was obtained in quantitative yield for CRA[4], PEO, and THPE. These results indicate that polymerization of BCA[n] ($n = 6$ and 8) affords botryosin-type polymers without formation of crosslinked structures, presumably because BCA[8] and BCA[6] have fixed cone-shaped structures, in which the hydroxy groups are located at the lower rim and their polymerization proceeded homogeneously.

These polymers, poly(BCA[n]-HDI) ($n = 6$ and 8), should be useful as new functional materials in the field of host–guest chemistry, because they contain a fixed hole in the main chain derived from BCA[n] ($n = 6$ and 8). We examined the liquid–liquid extraction of alkali metal cations such as Na⁺, K⁺, Rb⁺, and Cs⁺ using picrate salts from the aqueous phase into dichloromethane in the presence of the polymers by means of UV–vis spectroscopy (see SI). The extraction ratio was calculated from the decrease in the intensity of the peak at $\lambda_{max} = 355$ nm in the aqueous phase. The results are summarized, together with those for the gel product obtained by the reaction of CRA[4] and HDI, in Table 2. The synthesized poly(BCA[8]-HDI) and poly(BCA[6]-HDI) can enclose metal ions within the fixed holes of their "bunch of grape" structures. However, the gel product showed no significant ability to extract metal cations, presumably because the gel was produced by three-dimensional crosslinking reaction and does not contain fixed hole.

In summary, we have synthesized the soluble polymers poly(BCA[n]-HDI) ($n = 6$ and 8) in high yields by simple polymerization of *t*-butylcalix[n]arenes BCA[n] (A$_n$-type monomers) ($n = 6$ and 8) with HDI (B₂-type monomers). The

**Table 2.** Extraction of alkali metal cation (picrate salt) with polymers and gel[a]

| Ligand | poly(BCA[6]-HDI) | poly(BCA[8]-HDI) | Gel[b] |
|---|---|---|---|
| Na⁺ | 1 | 11 | <1 |
| K⁺ | 19 | <1 | <1 |
| Rb⁺ | 24 | 14 | <1 |
| Cs⁺ | 36 | 23 | <1 |

[a]Percentage cation extraction from an aqueous solution into dichloromethane by hosts polymers and gel at 25 °C. [b]Gel obtained by the reaction of CRA[4] and HDI.

$^1$H NMR, IR, and MALDI-TOF mass spectra, and AFM observation of the products indicated that poly(BCA[8]-HDI), which we designate as botryosin, consists of a cluster of nanoscale gels that are not three-dimensionally crosslinked. The synthesized poly(BCA[8]-HDI) and poly(BCA[6]-HDI) form inclusion complexes with alkali metal cations. We are currently examining the synthesis and properties of other soluble polymers derived from BCA[n] ($n = 4$, 6, and 8) and α,ω-functional monomers.

Supporting Information is available electronically on J-STAGE.

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