New Ring-Opening Polymerization via a π-Allylpalladium Complex. 5. Multibranching Polymerization of Cyclic Carbamate To Produce Hyperbranched Dendritic Polyamine

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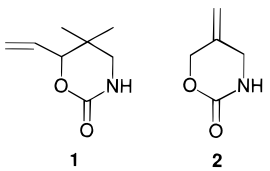
ABSTRACT: Hyperbranched dendritic polyamine consisting of primary, secondary (a nonbranching junction), and tertiary (a branching junction) amino moieties was produced by Pd-catalyzed decarboxylative ring-opening polymerization of 5-methyleneperhydro-1,3-oxazin-2-one (**2**) at 25 °C with the aid of benzylamine as the initiator. The degree of branching of the product polymer was dependent on the reaction solvent (60−80%). This is an example of multibranching polymerization where propagating ends multiply with the progress of the polymerization. Monomer **2** is activated by formation of a π-allylpalladium complex, which reacts with the propagating primary or secondary amino moiety. The number of amine protons that are the propagating ends increases by one at every step of the propagation.

Introduction

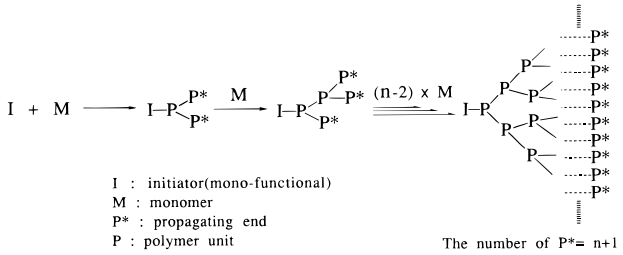
In a previous communication, we described a unique chain polymerization termed "multibranching polymerization (MBP)", whose general concept is shown in Scheme 1.[1] In MBP the number of propagating ends increases with the progress of the polymerization and, consequently, a hyperbranched dendritic polymer involving an initiator as the core is produced. Although MBP is carried out in one pot, the core structure of the product polymer is easily defined by the initiator added and the molecular weight is controllable by the feed ratio of initiator to monomer. When a macro initiator is employed, a graft or block copolymer having hyperbranched polymer segments is easily prepared.[2] These aspects distinguish MBP from other one-pot methods for preparation of hyperbranched polymers, i.e., (a) polycondensation or polyaddition of an AB_n type monomer[3,4] and (b) chain polymerization of a binary monomer possessing not only a site for polymerization but also that which is able to act as an initiator.[5] However, identically with these methods, also in MBP it is difficult to prepare a regularly branched polymer and the molecular weight of a product polymer is essentially polydisperse, which are different from a stepwise synthesis to produce dendrimer.[6]

MBP has been previously realized with cyclic carbamate **1**, which undergoes decarboxylative polymerization with the aid of a Pd catalyst to give hyperbranched dendritic polyamine.[1] This paper deals with further study of MBP employing cyclic carbamate **2**, 5-methyleneperhydro-1,3-oxazin-2-one, as the monomer, which successfully produced a hyperbranched dendritic polyamine.

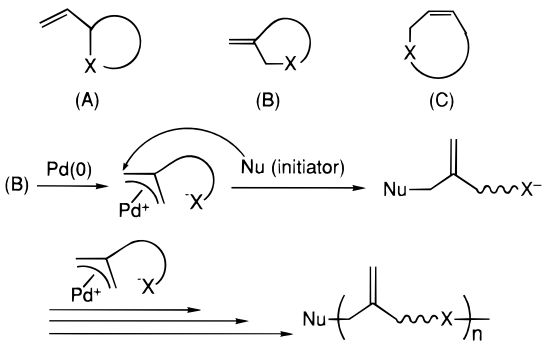


1 **2**

Scheme 1. Conceptional Scheme of Multibranching Polymerization (Multiple Coefficient = 2)



Scheme 2



This paper also fits in the series of our work on the new ring-opening polymerization via a π-allylpalladium complex (Scheme 2).[7] For this polymerization a monomer needs an appropriate leaving group at the allylic position and is activated by the oxidative addition of Pd(0) to form a π-allylpalladium intermediate, which is nucleophilically attacked by an initiator and a propagating end. A, B, and C are suitable types of monomers. All monomers previously described are of type A. Carbamate **2** is the first example of a type B monomer.

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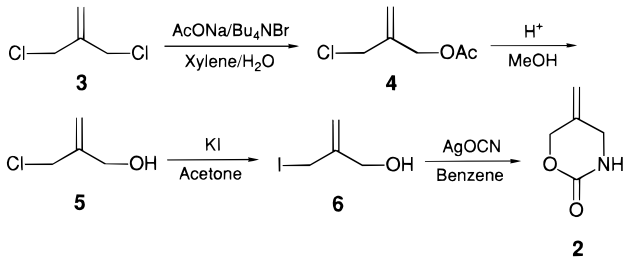
Scheme 3



Experimental Section

Materials and Measurements. $Pd_2(dba)_3{\cdot}CHCl_3$(dba: dibenzylideneacetone) was prepared as reported.[8] Shodex K-802 (Showa Denko) was employed as a column for GPC analysis using $CHCl_3$ as eluent. A calibration curve for GPC was made by use of polystyrene standards. VPO was carried out in $CHCl_3$ at 40 °C.

Monomer Synthesis. Monomer **2** was prepared in four steps (Scheme 3).

3-Chloro-2-methylenepropyl Acetate (4). A solution of 1,3-dichloro-2-methylenepropane (**3**) (37.74 g, 302 mmol) in xylene (50 mL) was stirred with potassium acetate (29.94 g, 305 mmol) in distilled water (50 mL) in the presence of tetrabutylammonium bromide (2.90 g, 9.0 mmol). After reflux for 2 h, the organic layer was separated and the aqueous layer was extracted with diethyl ether (30 mL × 3). The combined organic phase was dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. The fractional distillation of the residue gave **4** (75−80 °C/16 mmHg, 16.4 g, 36%): ^{1}H NMR (60 MHz, $CDCl_3$) δ 2.08 (s, 3H), 4.10 (s, 2H), 4.68 (s, 2H), 5.20−5.40 (br, 2H); IR (neat, cm^{-1}) 2950, 1750, 1655, 1445, 1380, 1235, 1040, 930, 760.

3-Chloro-2-methylene-1-propanol (5). A solution of **4** (9.44 g, 63.5 mmol) in methanol (40 mL) was refluxed in the presence of Amberlyst 15 (0.72 g) for 6 h. The resin was removed by filtration, and the filtrate was concentrated and distilled to give **5** (88−89 °C/38 mmHg, 5.4 g, 80%): ^{1}H NMR (60 MHz, $CDCl_3$) δ 1.70 (s, 1H), 4.15 (s, 2H), 4.25 (s, 2H), 5.26 (s, 2H); IR (neat, cm^{-1}) 3330, 2945, 1660, 1450, 1270, 1065, 1035, 920, 820, 760, 650.

3-Iodo-2-methylene-1-propanol (6). A solution of **5** (5.38 g, 50.5 mmol) in dry acetone (60 mL) was refluxed with potassium iodide (21.03 g, 126.7 mmol) for 8 h under a nitrogen atmosphere. Acetone was removed by evaporation under reduced pressure, and ethyl acetate (50 mL) and an aqueous NaCl solution (50 mL) were added. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (50 mL × 2). The combined organic phase was dried over anhydrous $MgSO_4$ and concentrated under reduced pressure to give **6** (8.63 g, 86%): ^{1}H NMR (60 MHz, $CDCl_3$) δ 2.24 (s, 1H), 4.02 (s, 2H), 4.36 (s, 2H), 5.24 (s, 1H), 5.41 (s, 1H); IR (neat, cm^{-1}) 3325, 2920, 1640, 1435, 1160, 1055, 915. This crude material was used in the next step without purification.

5-Methyleneperhydro-1,3-oxazin-2-one (2). All operations were carried out under a nitrogen atmosphere. To a stirred solution of **6** (7,79 g, 39.4 mmol) in dry benzene (30 mL) was slowly added silver isocyanate (6.45 g, 43.0 mmol) at room temperature. After 1 h, the fine precipitate was removed by use of barium filter paper and washed with dichloromethane. The solvent was evaporated from the filtrate to give a white solid, which was then recrystallized from dry dichloromethane (15 mL) with dry diethyl ether (10 mL) under nitrogen. The solid purified was collected by filtration and dried in vacuo (1.04 g, 23%): mp 90−91 °C; ^{1}H NMR (60 MHz, $CDCl_3$) δ 3.97 (s, 2H), 4.68 (s, 2H), 5.20 (s, 2H), 6.08 (br, 1H); IR (KBr, cm^{-1}) 3290, 2980, 1680, 1480, 1275, 1120, 1035, 915; MS (*m/e*) 113 (M^+), 68 ($[M - CO_2H]^+$), 41 ($C_3H_5^+$). Anal. Calcd: C, 53.09; H, 6.24; N, 12.38. Found: C, 52.32; H, 6.11; N, 12.29.

Typical Procedure for the Polymerization. To a solution of **2** (113 mg, 1.0 mmol), $Pd_2(dba)_3{\cdot}CHCl_3$ (5.2 mg, 5.0 × 10^{-3} mmol), and Ph_3P (10.5 mg, 4.0 × 10^{-2} mmol) in freshly distilled dry THF (1.5 mL) was added a THF solution (0.1 mL) of benzylamine (5.0 × 10^{-2} mmol) under argon. The conversion of **2** was followed by IR. The absorption due to the carbonyl group of **2** decreased in intensity with the progress of the polymerization, while the polymer produced precipitated. It took 2 days for complete conversion of **2** at room temperature. Butyl isocyanate (198 mg, 2.0 mmol) was added at 0 °C, and the mixture was stirred overnight at room temperature to give a homogeneous solution. Afterward, dry methanol (0.1 mL, 3.5 mmol) was added at 0 °C and the mixture was stirred for 3 h at room temperature. This solution was poured into Et_2O (50 mL) to precipitate the crude polymer. The precipitate collected by centrifugation was redissolved in chloroform. A trace of insoluble Pd black was removed by centrifugation. Pouring the supernatant into Et_2O precipitated the pale-yellow polymer, which was collected by centrifugation and dried in vacuo. ^{1}H NMR (400 MHz, $CDCl_3$, see Figure 2) δ 0.91, 1.32, 1.43, 2.83, 3.12, 3.46, 3.72, 3.78, 4.8−5.3, 5.9−6.7; ^{13}C NMR (100.6 MHz, $CDCl_3$, see Figure 3) δ 13.9, 20.2, 32.2, 32.7, 39.9, 40,8, 42,8, 49.8, 58.2, 113, 141.5−146, 158.6, 159.5; IR (KBr, cm^{-1}) 3349 (br), 3082, 2958, 2929, 2870, 2804, 1637 (br), 1567 (br), 1440, 1375, 1255, 1120, 992, 906, 647 (br).

Results and Discussion

Monomer **2** was prepared as colorless and moderately moisture sensitive crystals according to Scheme 3. The polymerization of **2** took place at 25 °C in THF, CH_2Cl_2, or DMSO with benzylamine as the initiator and $Pd_2(dba)_3{\cdot}CHCl_3/8Ph_3P$ as the catalyst (Table 1). Triphenylphosphine was a better ligand than bis(diphenylphosphino)ethane (dppe) for the polymerization of **2**. When dppe was employed (2 equiv for Pd), 60 °C was required for reaction.[9]

In all solvents studied, the polymer precipitates as the reaction progresses. Reactions were followed by IR. The absorption peak due to the carbonyl group of **2** gradually decreased in intensity and finally almost disappeared. The crude polymers produced were found to be insoluble in $CHCl_3$, MeOH, DMF, and water but soluble in MeOH/$CHCl_3$ (3/1 v/v) and in an aqueous solution of HCl. The polymers became virtually insoluble when stored dry.[10] To obtain information about the reaction, we measured the ^{1}H NMR spectrum of the reaction mixture whose solvent was removed by evaporation under reduced pressure and was immediately replaced with $CD_3OD/CDCl_3$ (3/1 v/v) (Figure 1). This chart reasonably indicated quantitative production of highly branched polyamine **7**, as expected (Scheme 4).

However, the above-described troublesome character of **7** prevented further investigation, so that **7** was treated with *n*-BuNCO, which is expected to react with both the primary and secondary amino moieties of **7**. The addition of *n*-BuNCO to the heterogeneous reaction mixtures gave homogeneous solutions. Unreacted excess *n*-BuNCO was inactivated with MeOH, and the resultant mixtures were poured into diethyl ether to precipitate the modified polymers **8**. For yields and molecular weights measured, see Table 1.

The molecular weight was evaluated by VPO and GPC calibrated against PSt standards. Every GPC $\bar{M}_n$ value is smaller than that by VPO. This is in agreement with the highly branched structure of **8**. The VPO $\bar{M}_n$ values were a little bigger than those calculated on the basis of the monomer−initiator feed ratio and the amount of *n*-BuNCO introduced. This is ascribable to fractionation during reprecipitation into diethyl ether.

When the amount of the initiator charged was increased, the $\bar{M}_n$ value of the product polymer was

Table 1. Pd-Catalyzed Ring-Opening Polymerization of 2[a]

run	solvent	initiator[b] (mol %)	time (h)	conv (%)	yield of **8**[c] (%)	$\bar{M}_n$(**8**) VPO	$\bar{M}_n$(**8**) GPC	$\bar{M}_n$(**8**) cal[d]	$\bar{M}_w/\bar{M}_n$(**8**) (GPC)	$\overline{DB}$(**8**)[e] ^{1}H[f]	$\overline{DB}$(**8**)[e] ^{13}C[f]
1	THF	5	48	100	75	3070	1800	2812	1.5	61	63
2	THF	10	48	100	75	2080	1400	1506	1.3	61	65
3	CH_2Cl_2	5	40	100	72	3030	1900	2772	1.4	67	68
4	DMSO	5	48	100	61	3040	2000	2696	1.5	81	77

[a] Conditions: see Experimental Section. [b] $PhCH_2NH_2$. [c] An Et_2O-insoluble part after treatment with *n*-BuNCO. [d] Calculated on the basis of the feed ratio (**2**/$PhCH_2NH_2$) and the amount of *n*-BuNCO introduced. [e] Degree of branching = number of tertiary amino group/(number of tertiary amino group + number of secondary amino group). [f] Calculated on the basis of relative peak intensity in ^{1}H or ^{13}C NMR spectra.

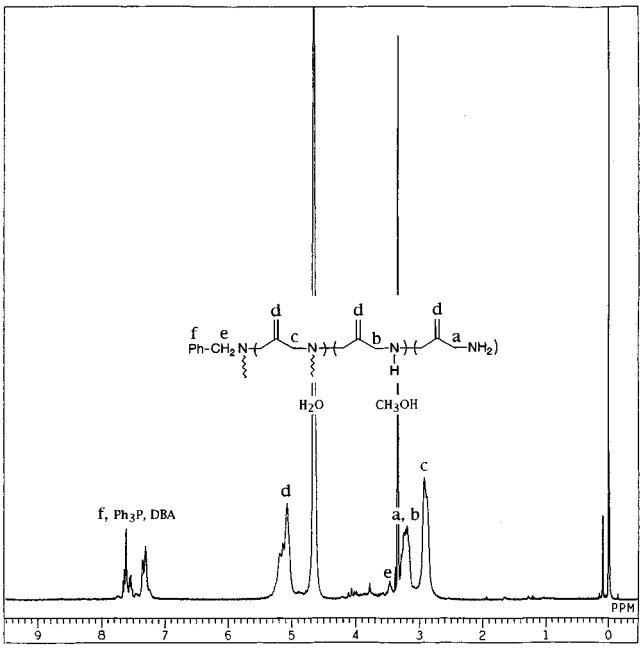


Figure 1. ^{1}H NMR spectrum ($CD_3OD/CDCl_3$ (3/1 v/v)) of the reaction mixture (run 1 in Table 1).

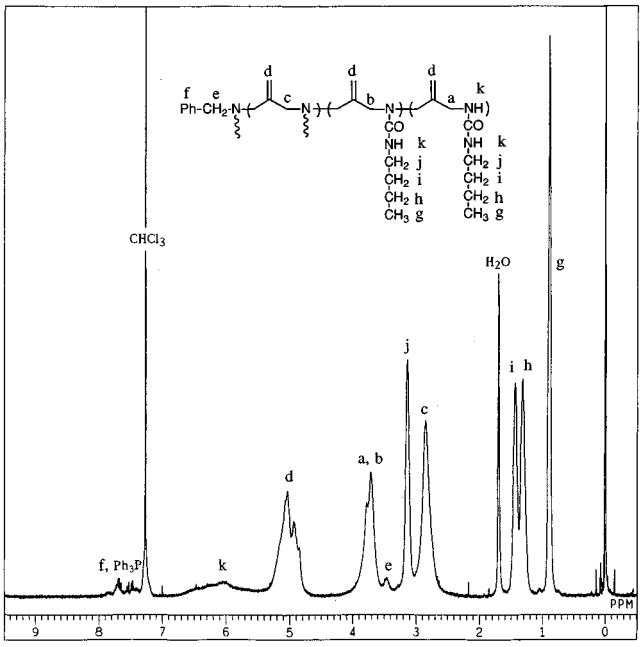
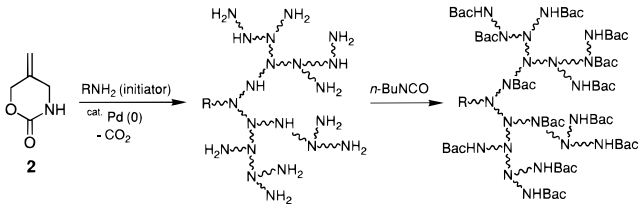


Figure 2. ^{1}H NMR spectrum ($CDCl_3$) of polymer **8** isolated (run 3 in Table 1).

Scheme 4



A simplified illustration of a representative model ($\overline{DP}$ = 20, $\overline{DB}$ = 67%) of the polymer structure.

The polymer unit =  , Bac = -CONH(*n*-Bu)

observed to decrease. However, this was not linearly due to the escape of a larger amount of the lower molecular weight polymer during the isolation. On the other hand, the decrease of the initiator charged is not related in a simple way to the increase of the molecular weight of the product polymer. The precipitation of the polymer during the polymerization made the reaction much slower and did not allow the complete conversion of the monomer. The use of a macro initiator that has a primary amino group resolves this problem by conducting the reaction in a homogeneous system throughout the polymerization.[2]

The control reactions without initiator were carried out. Reactions in THF and CH_2Cl_2 stop at an early stage: conv = 17% (THF), 18% (CH_2Cl_2). In DMSO, the monomer was almost completely consumed, but the product was insoluble in any solvent even after being treated with *n*-BuNCO. A similar phenomenon was also observed in the polymerization of **1**. Trace amounts of nucleophilic species may act as an initiator in these systems.[1]

The structures of the polymers modified with *n*-BuNCO were analyzed by IR, ^{1}H NMR, and ^{13}C NMR spectroscopy. The IR spectrum in $CHCl_3$ showed strong absorption peaks due to a urea moiety at 3349, 1637, and 1567 cm^{-1}. The ^{1}H and ^{13}C NMR spectra shown in Figures 2 and 3 with peak assignments supported the polymer structure **8** in Scheme 4. The peak assignments of the ^{13}C NMR spectrum were performed on the basis of 2D ^{1}H−^{13}C COSY NMR spectroscopy. Integral ratios between peaks in the ^{1}H NMR spectrum (Figure 2) indicated that the primary and secondary amine moieties of the original polymer **7** were quantitatively converted to the *N*-butylurea moieties by the reaction with *n*-BuNCO.

In Figure 2, there appeared a small peak ascribable to benzylic protons from the benzylamine initiator. However, unfortunately, incomplete peak separation did not permit calculation of the degree of polymerization accurately on the basis of integration of this peak.

The degree of branching ($\overline{DB}$) is the ratio of the number of tertiary amino moieties (=a branching junction) to the total number of secondary (=a nonbranching junction) and tertiary ones. Similarly, almost complete overlap of signals due to protons a and b did not allow

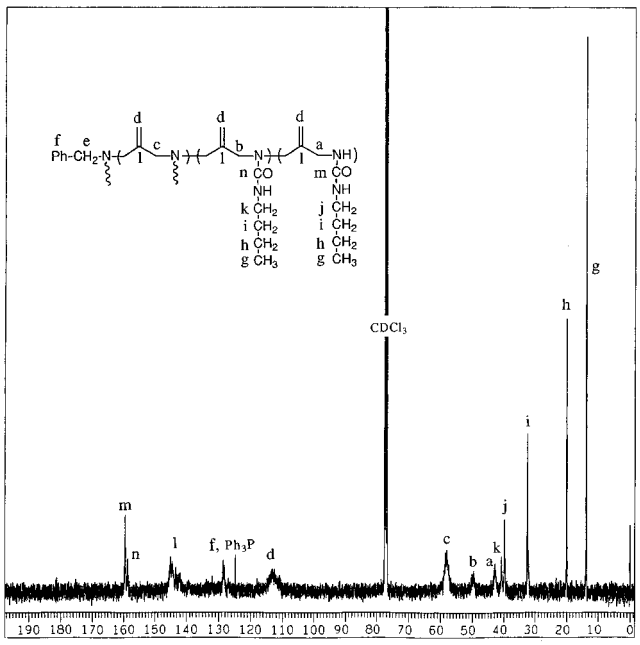
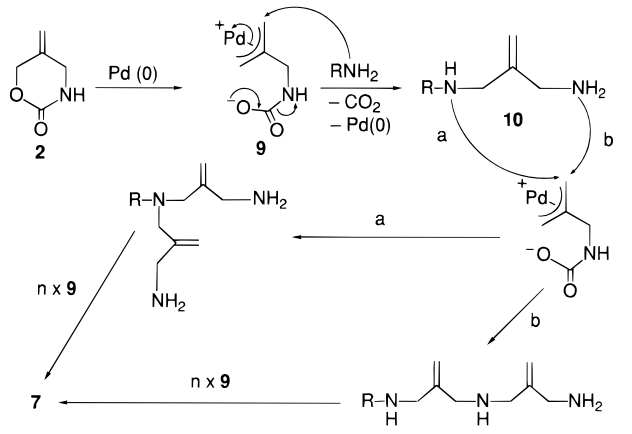


Figure 3. Gate decoupling ^{13}C NMR spectrum ($CDCl_3$) of polymer **8** isolated (run 3 in Table 1).

Scheme 5



direct comparison of peak intensities due to protons b and c for the evaluation of $\overline{DB}$. However, by taking into account the peak due to protons j together with those due to protons a, b, and c, it was possible to calculate this value according to the following equation: $\overline{DB} = (A_c/3)/[(A_c/3) + (A_{a,b} - A_j)]$, where A_α means the relative area of peak α in the ^1H NMR spectrum.[11] The values obtained were shown in Table 1. Alternatively, the gate-decoupling ^{13}C NMR spectrum excluding an NOE effect (Figure 3) yields these values by a direct comparison of peak intensities due to carbons b and c. The $\overline{DB}$ values calculated by the above two methods were in good agreement. The degree of branching was influenced by the polymerization solvent (Table 1). Polymer **8** prepared in a more polar solvent was more branched. This means that, during the polymerization, the secondary amino moiety has a higher nucleophilicity than the primary one in a polar solvent (vide infra).

Scheme 5 shows the reaction mechanism. During the polymerization, monomer **2** is converted to π-allylpalladium intermediate **9** by the oxidative addition of Pd(0) into the C–O bond. The allylic position of **9** is nucleophilically attacked by an initiator that is a primary or secondary amine to produce diamine **10** along with releasing CO_2 and Pd(0) that returns to activate **2**. Both of the amino groups of **10** also have the ability to react with **9** (paths a or b). This is the propagating step, where it is repeated that the primary, secondary, and tertiary amino groups are generated and then the former two react with **9**. Accordingly, the propagating end is the amine N–H groups whose protons transfer from end to end. It should be noticed that the number of these protons increases by one at every propagation reaction. This arises from the trick that the N–H group of **2**, which is protected by the carbonyl group, is activated by the propagation. According to the above process, including the multiplication of the propagating end, the hyperbranched dendritic polyamine having the initiator as the core is produced. Thus, this is MBP shown in Scheme 1.

As mentioned above, up to now, MBP has been achieved only in Pd-catalyzed ring-opening polymerization of cyclic carbamates such as **1** and **2**. To extend this limited scope, other polymerization systems for MBP are under investigation.

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(9) It forms a contrast with the polymerization of **1**, where dppe is a better ligand than Ph_3P. This is ascribable to the steric and electronic difference between two π-allylpalladium intermediates generated respectively from **1** and **2**; one is vinylic and the other is exomethylenic (see the mechanism).

(10) This phenomenon was observed also on the polymer produced from **1**. Generally, polyamine sometimes shows this character. This is possibly due to complex entanglement accompanied by intermolecular hydrogen bonds at many points of the polymer chains.

(11) The original primary, secondary, and tertiary amino moieties have one, two, and three allylic methylene groups, respectively. So, the relative peak area per one methylene group of the tertiary amino moiety is given by $A_c/3$. $A_{a,b}$ is the total peak area of two allylic methylene groups of the secondary amino moiety and one allylic methylene group of the primary one. The modification of the primary and secondary amino moieties with *n*-BuNCO produced two additional *N*-methylene groups whose protons are labeled j. Accordingly, the relative area of one methylene group of the secondary amino moiety is equal to $A_{a,b} - A_j$. As a result, a $\overline{DB}$ value is given by this equation.

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