

Synthesis of Novel Taxoids

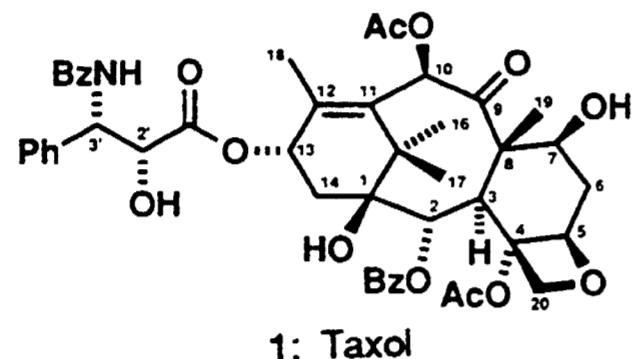
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Taxol (1), a naturally occurring substance isolated from the Pacific yew tree (*Taxus brevifolia*),¹ has recently been approved for clinical treatment of cancer patients. Its chemical synthesis and the synthesis of taxoid model systems have been the focus of extensive research efforts.²⁻⁵ Recent publications²⁻⁵ from these



laboratories disclosed a convergent approach to the taxoid family of compounds in which a Shapiro-type coupling⁵ is used as a means of joining rings A and C.⁶ In this communication we describe the application of this strategy to the synthesis of advanced taxoid systems containing the intact AB ring framework of taxol, including the side chain, and in which the CD ring system is replaced with an aromatic moiety.

According to this strategy, compound 9 (Scheme 1) was targeted as the initial key precursor to the designed molecules. Its construction is outlined in Scheme 1. Hydrazone 2 was coupled with aldehyde 3 as previously described with similar systems⁵ leading to racemic 4 in 86% yield. Directed epoxidation of 4 using the Sharpless protocol⁷ gave hydroxy epoxide 5 in 90% yield. Regioselective opening of the oxirane ring in 5 using LiAlH₄ was accompanied by desilylation, leading to the corresponding tetraol, which was selectively silylated with *tert*-butyldimethylsilyl chloride, furnishing diol 6 in 75% overall yield. The molecular framework of the intermediates was then rigidified in preparation for the ring closure by carbonate formation through exposure to carbonyliimidazole (95%) affording compound 7, which was then desilylated and oxidized⁸ to give dialdehyde 8 (89% overall yield). McMurry coupling⁹ of the aldehyde groups in 8 produced compound 9 in 53% yield, together with a mixture of three other isomeric diols of gross structure 9 (ca. 20% total yield) and product 9', resulting from a 1,4-participation of the enone functionality in 8 (15% yield). The major isomer 9, mp 251 °C dec (methylene

(1) Wani, M. C.; Taylor, M. E.; Coggan, P.; McPhail, A. T. *J. Am. Chem. Soc.* 1971, 93, 2325.

(2) For a review, see: Nicolaou, K. C.; Guy, R. K.; Dai, W.-M. *Angew. Chem., Int. Ed. Engl.* 1994, 33, 15 and references cited therein.

(3) Nicolaou, K. C.; Hwang, C.-K.; Sorensen, E. J.; Claiborne, C. F. *J. Chem. Soc., Chem. Commun.* 1993, 1017.

(4) Nicolaou, K. C.; Liu, J.-J.; Hwang, C.-K.; Dai, W.-M.; Guy, R. K. *J. Chem. Soc., Chem. Commun.* 1993, 1118.

(5) Nicolaou, K. C.; Yang, Z.; Sorensen, E. J.; Nakada, N. *J. Chem. Soc., Chem. Commun.* 1993, 1024.

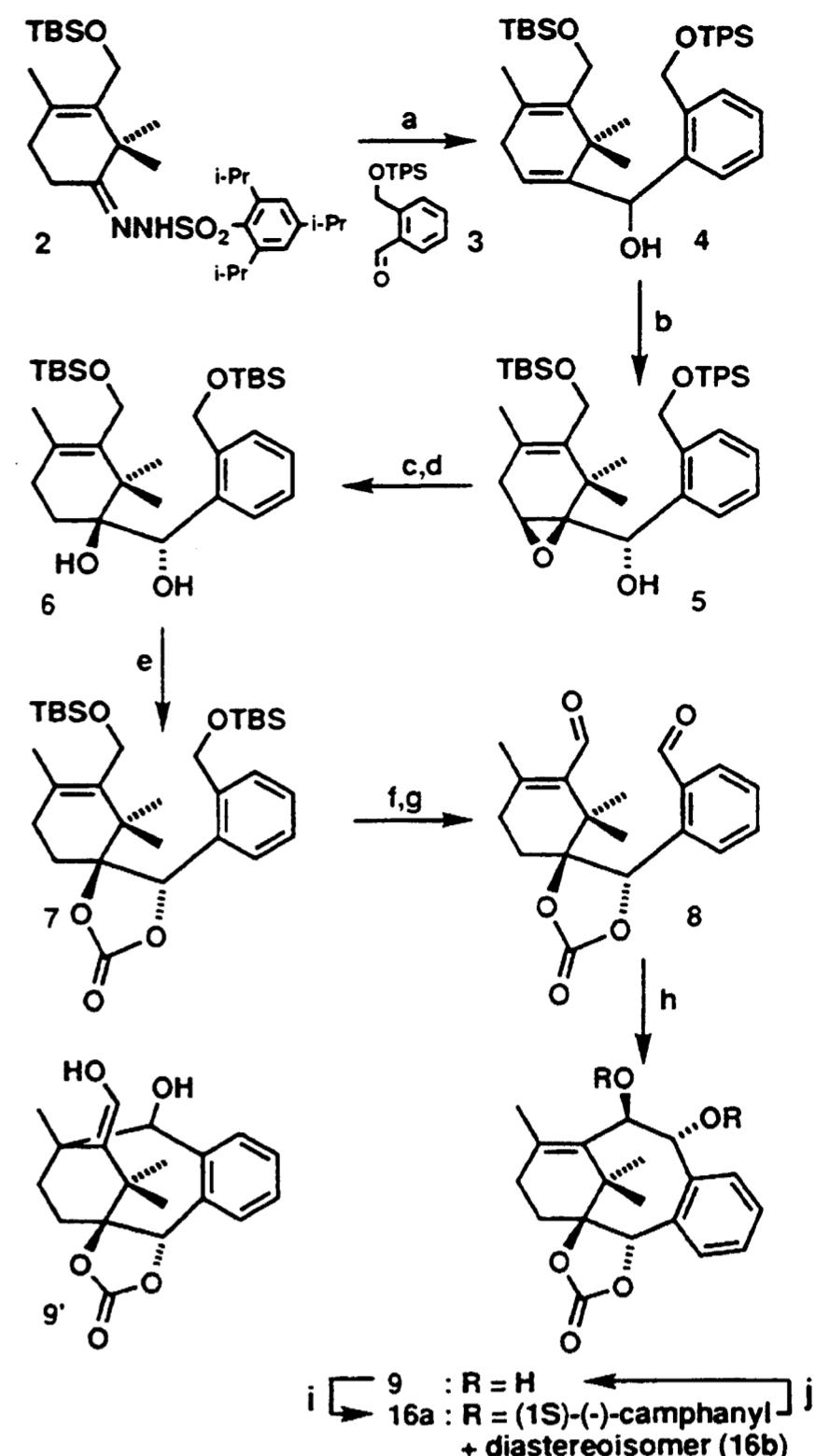
(6) This strategy was later used by others to accomplish similar couplings: Di Grandi, M. J.; Jung, D. K.; Krol, W. J.; Danishefsky, S. J. *J. Org. Chem.* 1993, 58, 4989. Maskers, J. J.; Jung, D. K.; Bornmann, W. G.; Danishefsky, S. J. *Tetrahedron Lett.* 1993, 34, 7253.

(7) Sharpless, K. B.; Verhoeven, T. R. *Aldrichimica Acta* 1979, 12, 63.

(8) Griffith, W. P.; Ley, S. V. *Aldrichimica Acta* 1990, 23, 13.

(9) McMurry, J. E. *Chem. Rev.* 1989, 89, 1513. McMurry, J. E.; Rico, J. G.; Leckta, T. C. *J. Org. Chem.* 1989, 54, 3748. McMurry, J. E.; Rico, J. G. *Tetrahedron Lett.* 1989, 30, 1169. See also: Kende, A. S.; Johnson, S.; San Filippo, P.; Hodges, J. C.; Jungheim, L. N. *J. Am. Chem. Soc.* 1986, 108, 3513.

Scheme 1. Synthesis of Key Intermediate 9^a



^a Reagents and conditions: (a) 2 (1 equiv), *n*-BuLi (2.1 equiv), THF, -78 → 25 °C; cool to 0 °C and add 3 (1.1 equiv), 30 min, 86%; (b) *t*-BuOOH (1.5 equiv), VO(acac)₂ (0.05 equiv), benzene, 25 °C, 5 h, 90%; (c) LiAlH₄ (5 equiv), Et₂O, reflux, 4 h, 75%; (d) TBS-Cl (2.1 equiv), imidazole (2.5 equiv), CH₂Cl₂, 25 °C, 1 h, 100%; (e) carbonyliimidazole (10 equiv), acetonitrile, reflux, 2 h, 95%; (f) TBAF (4 equiv), THF, 25 °C, 2 h, 100%; (g) TPAP (0.05 equiv), NMO (5 equiv), CH₂Cl₂, 25 °C, 89%; (h) TiCl₃(DME)_{1.5} (20 equiv), Zn-Cu (40 equiv), DME, reflux, 3 h, then add 8 at 55 °C via syringe pump, 1-h addition, then heat for additional 2 h, 53% of 9, plus 20% total of two unassigned stereoisomers, plus 15% of 9'; (i) (1S)-(-)-camphanic chloride (6 equiv), Et₃N (10 equiv), DMAP (0.05 equiv), CH₂Cl₂, 25 °C, 2 h, 100% (1:1, 16a:16b); (j) K₂CO₃ (0.05 equiv), MeOH, 25 °C, 2 h, 100% (enantiomerically pure 9).

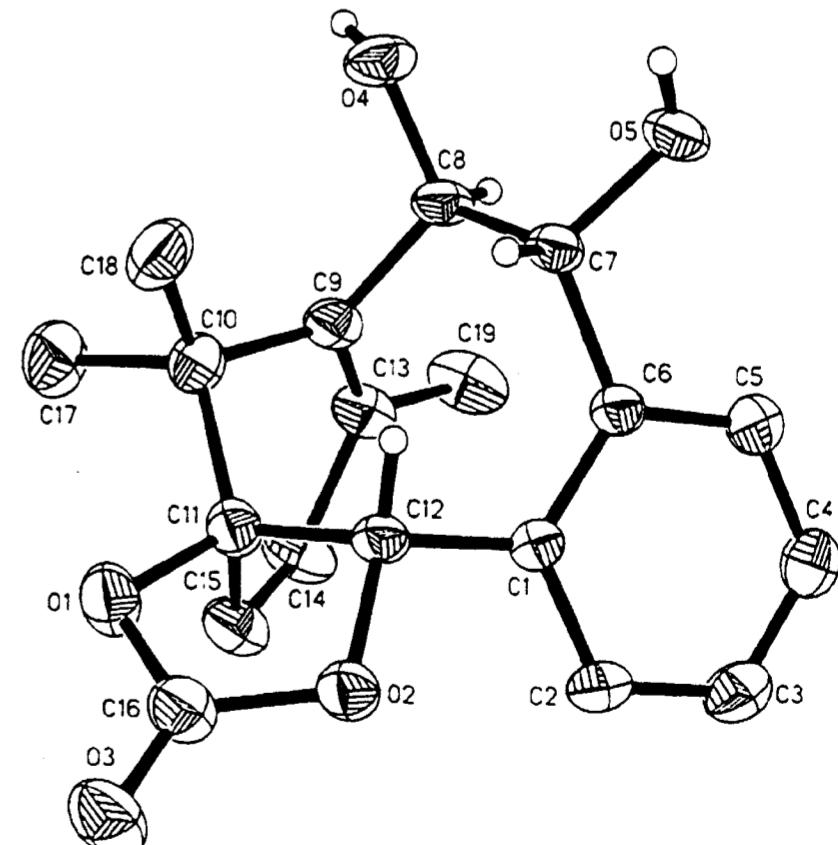


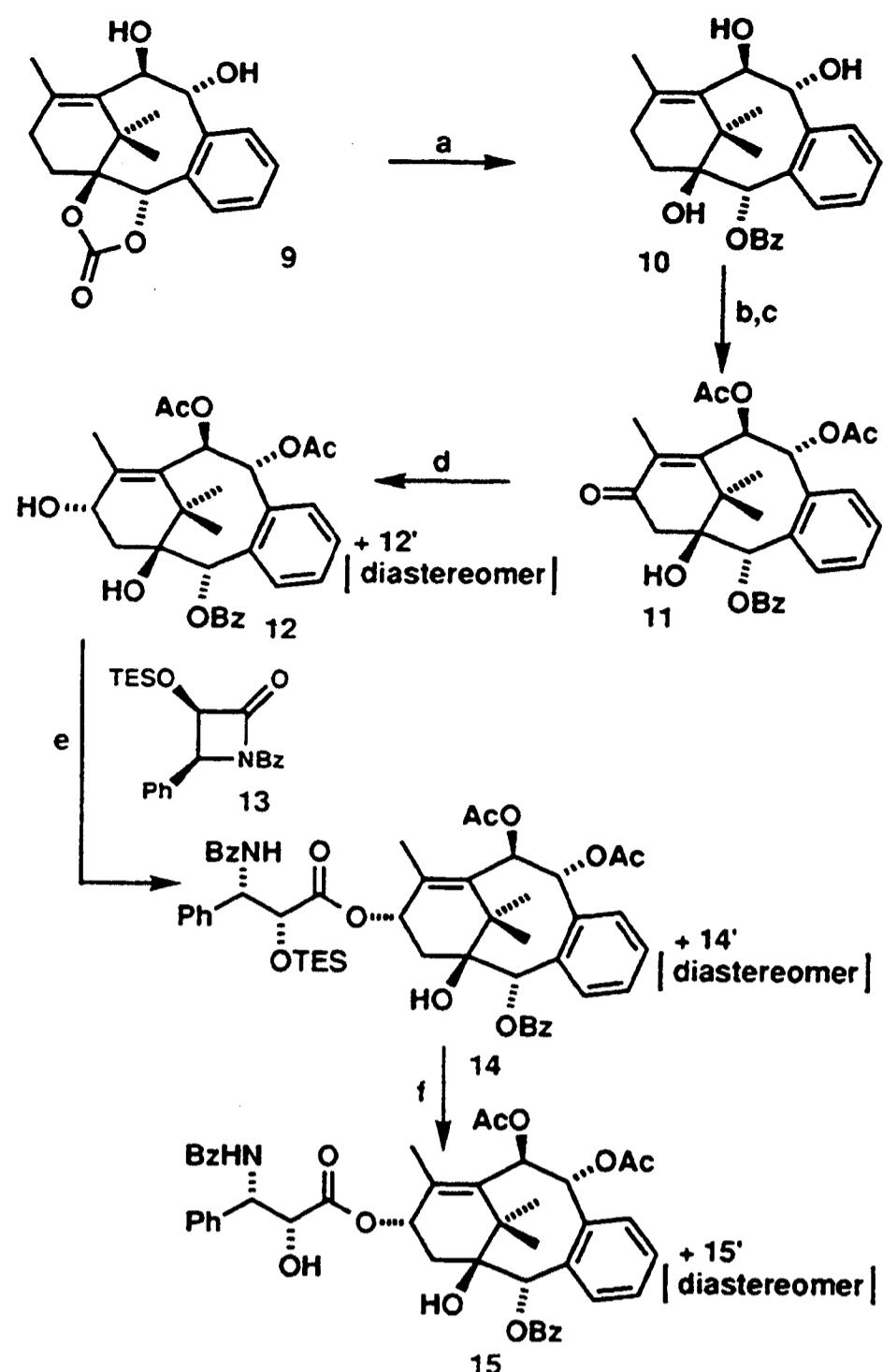
Figure 1. ORTEP drawing of 9.

chloride-hexane), was subjected to X-ray crystallographic analysis, revealing the indicated stereochemistry (see ORTEP drawing, Figure 1).¹⁰

Carbonate 9 reacted with excess PhLi at low temperature to form, in a remarkably clean and regioselective fashion, the

(10) This X-ray crystallographic analysis was carried out by Dr. Raj Chadha of The Scripps Research Institute.

Scheme 2. Synthesis of Taxoid 15 and Its Diastereomer 15'



^a Reagents and conditions: (a) PhLi (10 equiv), THF, -78 °C, 30 min, 80%; (b) Ac₂O (2.5 equiv), Et₃N (2.8 equiv), DMAP (0.05 equiv), CH₂Cl₂, 25 °C, 1 h, 100%; (c) PCC (30 equiv), Celite, NaOAc (20 equiv), benzene, reflux, 2 h, 55%; (d) NaBH₄ (20 equiv), MeOH, 0 °C, 20 min, 90% (8:1 mixture α to β isomers); (e) 12 (1 equiv), 13 (2.0 equiv), NaN(SiMe₃)₂ (3 equiv), THF, -78 °C, 30 min, 33% of 14, plus 33% of 14', plus 10% recovered starting material (73% combined yield based on 90% conversion); (f) HF-pyr (2.0 equiv), THF, 25 °C, 2 h, 90%.

secondary benzoate 10 in 80% yield (Scheme 2) (see Note Added in Proof). The later compound was selectively and quantitatively acetylated by exposure to Ac₂O-Et₃N, furnishing the corresponding diacetate, which was then oxidized with PCC-NaOAc-Celite to enone 11 (55% yield). Reduction of enone 11 with NaBH₄ in methanol resulted in the formation of two isomeric alcohols in *ca.* 8:1 ratio and 90% total yield. The two isomers were separated chromatographically (silica, benzene: EtOAc mixtures) leading to pure isomers 12 and 12' (12, major, R_f = 0.4; 12', minor, R_f = 0.35). The major compound (12) was assigned the indicated α -stereochemistry on the basis of NMR spectroscopic data.¹¹ Finally, attachment of the taxol side chain onto the α -isomer 12 was accomplished using the Holton-Ojima method.^{12,13} Thus, reaction of 12 with β -lactam 13¹³ at -78 °C in the presence of NaN(SiMe₃)₂ resulted in the formation of two diastereoisomers 14 (R_f = 0.45, silica, 80% ether in petroleum ether; $[\alpha]_D^{22}$ = 26.67°, *c* 1.5, CHCl₃) and 14' (R_f = 0.32, silica, 80% ether in petroleum ether; $[\alpha]_D^{22}$ = -24.43°, *c* 1.4, CHCl₃) in a combined yield of 73% (*ca.* 1:1 ratio) at *ca.* 90% conversion. Chromatographic separation of the two diastereoisomers, followed by desilylation, resulted in the formation of taxoid 15 (R_f = 0.43, silica, ether; $[\alpha]_D^{22}$ = 52.33°, *c* 0.3, CHCl₃) and its diastereoisomer 15' (R_f = 0.32, silica, ether; $[\alpha]_D^{22}$ = -16.00°, *c* 0.5, CHCl₃) in 90% yield. In order to secure stereochemical assignments, diol 9 was resolved through its diastereomeric dicamphanyl esters¹⁴ 16a and 16b, which were separated chromatographically (16a, R_f = 0.58, silica, 15% EtOAc in benzene; 16b, R_f = 0.50, silica, 15% EtOAc in benzene). The less polar isomer (16a) was hydrolyzed under basic conditions to afford optically active diol

9 ($[\alpha]_D^{22}$ = 92.00°, *c* 0.4, CHCl₃), whose X-ray crystallographic analysis (see ORTEP drawing, Figure 1) confirmed its absolute stereochemistry. This diol was then taken through the described sequence to enantiomerically pure 14.

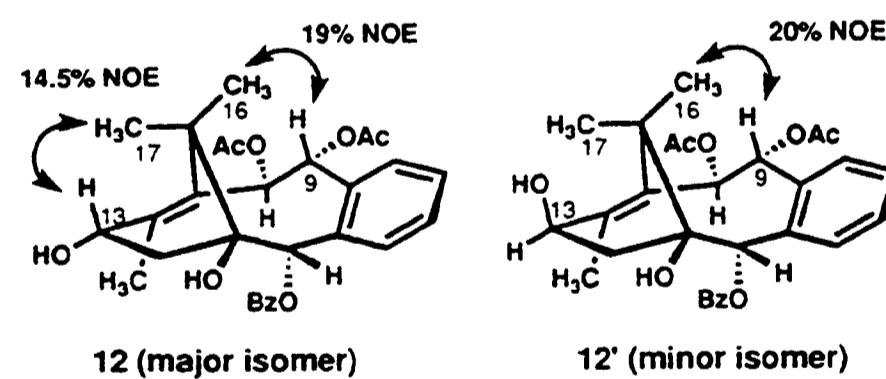
Interestingly, compound 15 exhibited significant cytotoxicity against a variety of tumor cell lines,¹⁵ whereas its diastereoisomer (15') showed essentially no cytotoxicity under the same conditions. These results define further structural parameters for the design of bioactive taxoids and provide a synthetic entry to such compounds.¹⁶

Note Added in Proof: For a total synthesis of taxol from these laboratories, see: Nicolaou, K. C.; Yang, Z.; Liu, J. J.; Ueno, H.; Nantermet, P. G.; Guy, R. K.; Claiborne, C. F.; Renaud, J.; Couladouros, E. A.; Paulyannan, K.; Sorensen, E. J. *Nature* 1994, 367, 630. For the use of PhLi to form the C-2 benzoate of taxol, see: Nicolaou, K. C.; Nantermet, P. G.; Ueno, H.; Guy, R. K. *J. Chem. Soc., Chem. Commun.* 1994, 295.

Acknowledgment. We thank Professor Ojima for useful discussions relating to taxol side chain attachment, Dr. Raj Chadha for the X-ray crystallographic analysis, and Dr. Wolfgang Wrasidlo for the cytotoxicity data. C.F.C. thanks Mr. Richard Staley for a generous graduate student fellowship (1992-1993) and Glaxo for a graduate student fellowship (1993-1994), P.G.N. thanks Rhone-Poulenc Rorer for a postdoctoral fellowship (1993), and E.J.S. thanks the Organic Division of the American Chemical Society for a graduate student fellowship (1992-1993). This work was supported by The Scripps Research Institute.

Supplementary Material Available: Schemes for synthesis of compounds 2 and 3 and listings of selected physical data for compounds 4, 5, 8-10, 12, 14, 14', 15, and 15' (12 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(11) The indicated assignments were made on the basis of the following observations. 12 (major isomer): Irradiation at δ 1.09 (16-CH₃) resulted in 20% NOE enhancement at δ 5.81 (9-H), suggesting that 12 adopts a conformation wherein the 16-CH₃ and the 9-H are in close proximity as shown in the illustration. Irradiation at δ 1.03 (17-CH₃) resulted in 14.5% NOE enhancement at δ 4.33 (13-H), suggesting a β orientation for 13-H as indicated. 12' (minor isomer): Irradiation at δ 1.0 (16-CH₃) resulted in 19% NOE enhancement at δ 5.73 (9-H), supporting the conformation shown. Irradiation at δ 1.25 (17-CH₃) resulted in no NOE with 13-H as expected for 12'.



(12) Holton, R. A. *Eur. Pat. Appl. EP 400,971, 1990; Chem. Abstr.* 1990, 114, 164568q.

(13) Ojima, I.; Sun, C. M.; Zucco, M.; Park, Y. H.; Duclos, O.; Kuduk, S. *Tetrahedron Lett.* 1993, 34, 4149. Ojima, I.; Habus, I.; Zucco, M.; Park, Y. M.; Sun, C. M.; Brigaud, T. *Tetrahedron* 1992, 48, 6985. We thank Professor Ojima for a generous gift of β -lactam 13.

(14) Gerlach, H. *Helv. Chim. Acta* 1978, 61, 2773.

(15) Cell line (IC₅₀ M value): HT-29 (1.29×10^{-7}); Ovcar 3 (2.80×10^{-7}); UCLA-P3 (2.96×10^{-7}); A-549 (6.45×10^{-7}); L-1210 (1.11×10^{-6}); SIH-A (1.29×10^{-6}); 786-0 (1.93×10^{-6}); SK-Mel-28 (2.71×10^{-6}); SK-NH-SH (4.91×10^{-6}); BT-549 (5.30×10^{-6}). The corresponding values for taxol are as follows: HT-29 (5.1×10^{-8}); Ovcar 3 (6.2×10^{-10}); UCPLA-P3 (6.4×10^{-9}); A-549 (1×10^{-12}); L-1210 (7.0×10^{-9}); SIH-A (1×10^{-12}); 786-0 (2.2×10^{-6}); SK-Mel-28 (1.2×10^{-7}); SK-NH-SH (6.2×10^{-10}); BT-549 (5.0×10^{-10}).

(16) All new compounds exhibited satisfactory spectral and mass data. Yields refer to spectroscopically and chromatographically homogeneous materials.