Synthetic Methods

DOI: 10.1002/ange.201400944

Stereocontrolled Synthesis of Adjacent Acyclic Quaternary-Tertiary Motifs: Application to a Concise Total Synthesis of (−)-Filiformin**

*Daniel J. Blair, Catherine J. Fletcher, Katherine M. P. Wheelhouse, and Varinder K. Aggarwal**

Abstract: *Lithiation/borylation methodology has been developed for the synthesis of acyclic quaternary-tertiary motifs with full control of relative and absolute stereochemistry, thus leading to all four possible isomers of a stereodiad. A novel intramolecular Zweifel-type olefination enabled acyclic stereocontrol to be transformed into cyclic stereocontrol. These key steps have been applied to the shortest enantioselective synthesis of (−)-filiformin to date (9 steps) with full stereocontrol.*

Natural products containing quaternary stereogenic centers flanked by additional stereogenic centers, often embedded in fused or bridged ring systems, are ubiquitous in nature (Figure 1). Their varied structures and complexity have

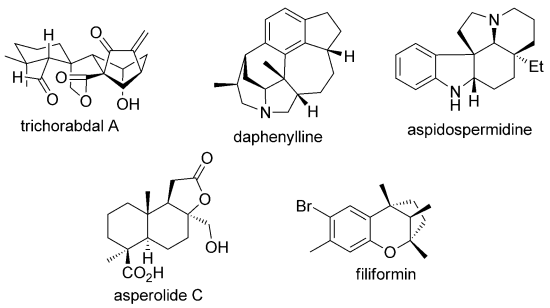
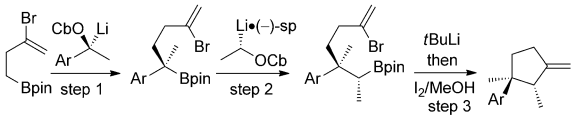


Figure 1. Natural products featuring adjacent quaternary-tertiary stereocenters.

stimulated a range of synthetic strategies for their synthesis.[1] A common strategy in many syntheses is to initially construct the ring(s) and then to use the ring system to control stereochemistry around its periphery. Whilst often efficient, this strategy can be limiting as it is based on substrate control. A potentially more flexible, but underutilized strategy involves constructing an acyclic molecule with control of stereochemistry through reagent control and then to build the ring afterwards. In this way, stereocontrol can be essentially dialed in. However, whilst acyclic stereocontrol can be straightforward for many substrates, for molecules bearing quaternary-tertiary motifs this poses a considerable synthetic challenge.

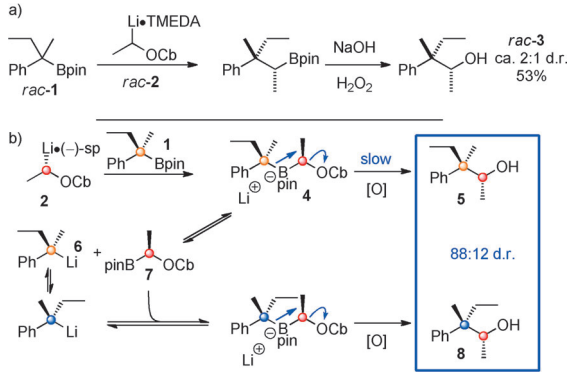
Our recent methodology for acyclic stereocontrol[2] involves the reaction of primary/secondary lithiated carbamates with boronic esters and its potential strategic application in the synthesis of cyclic quaternary-tertiary motifs is illustrated in Scheme 1. In this strategy we proposed to carry



Scheme 1. Proposed route to all-carbon quaternary stereocenters with adjacent stereocenters. Cb = CON(*i*Pr)$_2$, pin = pinacolato, (−)-sp = (−)-sparteine.

out sequential homologations with a secondary carbamate (step 1)[3] followed by a primary carbamate (step 2)[4] to construct quaternary-tertiary boronic esters. We then proposed to carry out an intramolecular Zweifel-type olefination[5] reaction (step 3) to construct the ring. Steps 2 and 3, which are key to this strategy, had not been previously reported. Herein we describe our success in developing these reactions and applying them to a short, stereocontrolled synthesis of (−)-filiformin.

Our initial studies began with the homologation of the tertiary boronic ester *rac*-**1** with lithiated carbamate *rac*-**2** which was generated by deprotonation of ethyl carbamate with *s*BuLi at −78 °C in the presence of TMEDA (Scheme 2a). After oxidation *rac*-**3** was isolated in 53 % yield and 2:1



Scheme 2. a) Racemic homologation of *rac*-**1**. b) Homologation of **1** with enantioenriched reaction partners and proposed mechanism for formation of diastereoisomers.

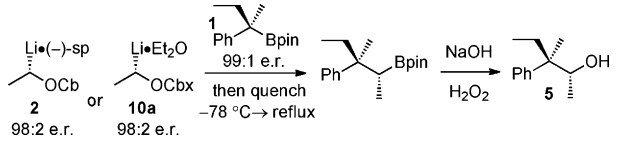
[*] D. J. Blair, Dr. C. J. Fletcher, Prof. Dr. V. K. Aggarwal
School of Chemistry, University of Bristol
Cantock's Close, Bristol, BS8 1TS (UK)
E-mail: v.aggarwal@bristol.ac.uk
Dr. K. M. P. Wheelhouse
GlaxoSmithKline UK LtD
Gunnels Wood Road, Stevenage, Herts, SG1 2NY (UK)

[**] We thank the EPSRC, GSK, and the European Research Council (FP7/2007-2013, ERC grant no. 246785) for financial support.
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201400944.

d.r., thus showing that there were no appreciable matched/mismatched effects.

When we carried out the reaction with the enantioenriched boronic ester **1** and enantioenriched lithiated carbamate **2** we were expecting to selectively form a single diastereomeric ate complex **4** which should then rearrange to give the single diastereomer **5** (Scheme 2b). However, when we carried out this reaction we obtained **5** together with **8** in a ratio of 88:12, albeit with perfect e.r. (Table 1, entry 1).

Table 1: Optimization of conditions for the homologation of the tertiary boronic ester **1** with **2**/**10a**.



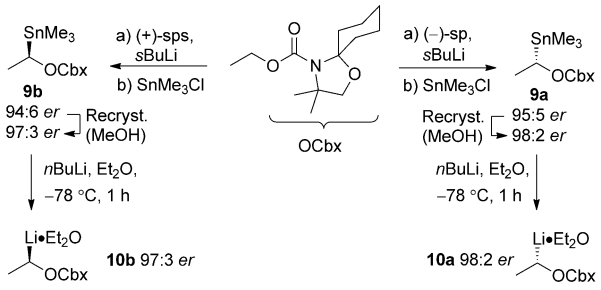
Entry	Carbamate	Quench	d.r.[a]	e.r.[b]	Yield [%][c]
1	**2**		88:12 (**5**/**8**)	>99:1	n.d.
2[d]	**2**		88:12(**5**/**8**)	n.d.	n.d.
3	**2**	MeOH	98:2 (**5**/*ent*-**8**)	>99:1	28
4	**2**	$MgBr_2$/MeOH	98:2(**5**/*ent*-**8**)	>99:1	22
5	**2**	AllylBr	98:2 (**5**/*ent*-**8**)	>99:1	48
6	*ent*-**2**[e]	AllylBr	1:99 (**5**/*ent*-**8**)	>99:1	32[f]
7	**10a**	AllylBr	98:2 (**5**/*ent*-**8**)	>99:1	73

[a] Determined by GCMS. [b] Determined by HPLC using a chiral stationary phase. [c] Yield of isolated **5**. [d] Neopentyl glycol boronic ester used. [e] (+)-sparteine surrogate used in place of (−)-sparteine. [f] Yield of isolated *ent*-**8**.

It was unclear at this point which of the two stereogenic centers was epimerizing, and so further experiments were conducted. Thus, the enantioenriched lithiated carbamate **2** was reacted with *rac*-**1** and vice versa. Oxidation and analysis of the secondary alcohol products by HPLC using a chiral stationary phase enabled us to map the fate of each stereogenic center individually during the homologation process (see the Supporting Information). From these experiments we determined that partial racemization had occurred, not in the sensitive organolithium **2** bearing the secondary center which is undergoing significant transformations, but at the static quaternary stereogenic center derived from the boronic ester, thus leading to the minor diastereoisomer **8**. The mechanism for its formation is shown in Scheme 2b. After formation of the boronate complex **4**, 1,2-metallate rearrangement will give the major isomer **5**. If this rearrangement is slow, competing fragmentation to the benzylic carbanion **6** can occur. Racemization of **6**, re-addition to boronic ester **7**, and rearrangement then leads to the minor diastereoisomer **8**. In support of this mechanism, **7** was also isolated in high e.r..

In an attempt to reduce the undesired fragmentation of **4** the less hindered neopentyl glycol boronic ester was tested, since related neopentyl boronate complexes have been shown to be less prone to reversibility than the corresponding pinacol boronates.[3a,6] However, homologation of neopentyl-**1** gave similar results to that of the pinacol ester (Table 1, entry 2). As an alternative, we sought to trap the anion **6** as it was formed with an electrophile, thus preventing its re-addition to the boronic ester (Table 1, entries 2–5). Of the electrophiles tested allyl bromide proved to be highly effective, thus leading to **5** in high d.r. and e.r. (entry 5). The relative stereochemistry of **5** was determined by X-ray crystallography.[7]

However, the yield was only moderate (48%) and fell further (32%) when we attempted to synthesize the other diastereoisomer of **5** by using O'Brien's (+)-sparteine surrogate [(+)-sps][8] in place of (−)-sparteine in the lithiation step (Table 1, entry 6). We reasoned that the bulky diamine was inhibiting the addition process and therefore explored diamine-free conditions [generating the organolithium **10a** by tin–lithium exchange of the corresponding stannane **9a**] to make the carbanion less hindered.[9] This led to a considerably higher yield (73%; Table 1, entry 7). The stannanes **9a** and **9b** were easily obtained in high e.r. as shown in Scheme 3.[10]

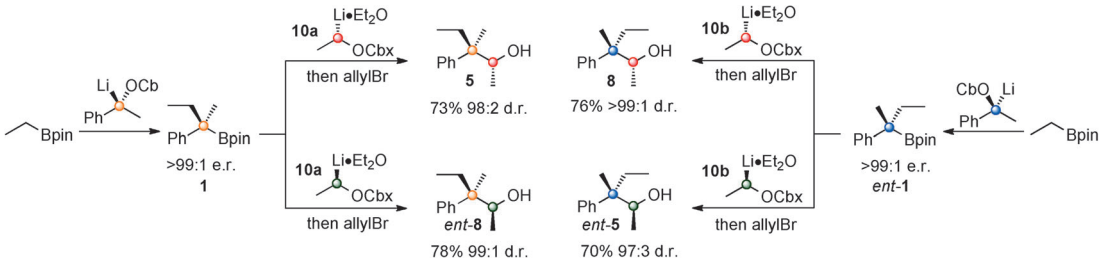


Scheme 3. Preparation of diamine-free lithiated carbamates **10a** and **10b**. OCbx = 3,3-dimethyl-1-oxa-4-azaspiro[4.5]decane-4-carboxylate, (+)-sps = (+)-sparteine surrogate.

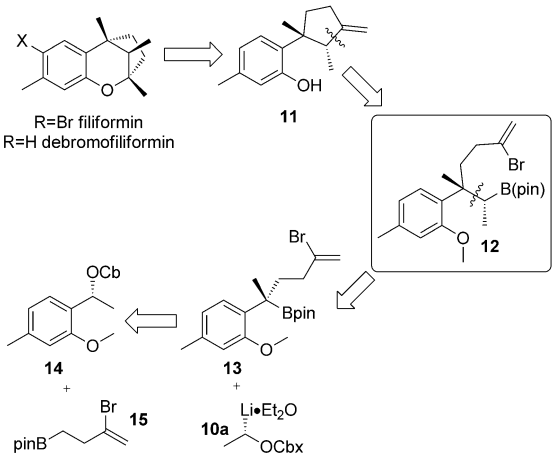
With these optimum reaction conditions we moved on to synthesize the remaining three stereoisomers (Scheme 4). Reaction of the enantiomer of the lithiated carbamate **10b** with **1** gave alcohol *ent*-**8** in 99:1 d.r. and greater than 99:1 e.r. Reaction of the opposite enantiomer of the boronic ester *ent*-**1** with the pair of lithiated carbamates **10a** and **10b** gave the remaining isomers of the series in good yield and with essentially perfect stereocontrol (Scheme 4). It is interesting to note that even in the mismatched cases (forming **5** and *ent*-**5**) very high diastereocontrol (>97:3) was still observed.

We then sought to apply our methodology to a total synthesis of the sesquiterpene (−)-filiformin. Disconnecting the phenol ether of debromofiliformin leads back to 3-hydroxylaurene (**11**), which itself could potentially be obtained from an intramolecular Zweifel-type olefination of **12** (Scheme 5). This key intermediate could be synthesized using the above methodology through reaction of **10a** with the tertiary boronic ester **13**. The boronic ester **13** could in turn be prepared by a lithiation/borylation of the known carbamate **14** and primary boronic ester **15**.

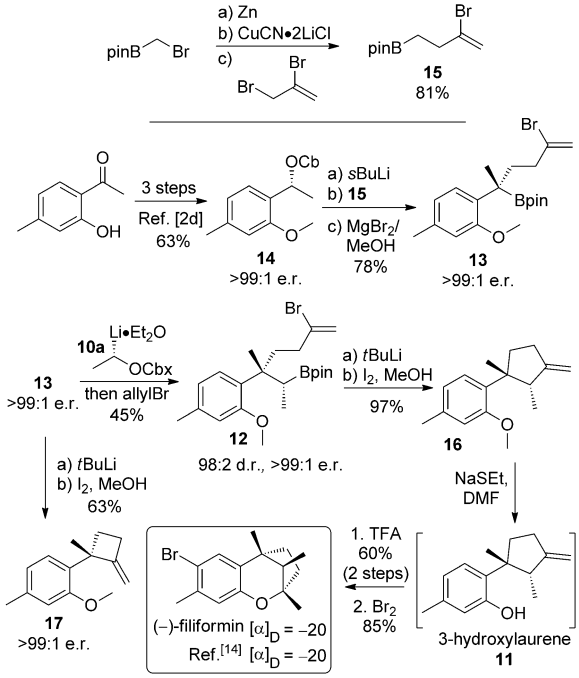
The boronic ester **15** was prepared from bromomethyl boronic acid pinacol ester and 2,3-dibromo-1-propene to give **15** in 81% yield using a procedure described by Knochel (Scheme 6).[11] The carbamate **14** was prepared in three steps starting from 2′-hydroxy-4′-methyl acetophenone as previ-



Scheme 4. Homologation of tertiary boronic esters with lithiated carbamates under diamine-free conditions to produce adjacent quaternary-tertiary stereocenters. Reactions were performed on 1 mmol of **1**/ent-**1** using 1.5 mmol of **10a**/**10b.**



Scheme 5. Retrosynthetic analysis of (−)-filiformin.



Scheme 6. Total synthesis of (−)-filiformin. TFA = trifluoroacetic acid.

ously described.[2d] The lithiation/borylation of **14** with **15** proceeded smoothly to give **13** in 78% yield with complete enantioselectivity.

The tertiary boronic ester **13** is especially hindered because of the *ortho*-methoxy group and the long alkyl chain so formation of the boron ate complex was expected to be even more challenging than in the model system. Nevertheless, under our optimized reaction conditions using **10a** we were able to obtain **12** in 45% yield with 98:2 d.r. and in perfect e.r..[12] Using the reaction conditions shown in entry 5 of Table 1, no product was obtained, thus highlighting the advantages of the diamine-free conditions with especially hindered substrates.

We then sought to perform the intramolecular Zweifel-type olefination of **12**. Addition of *t*BuLi to a solution of **12** in THF at −78 °C and subsequent addition of I_2 in MeOH gave the cyclopentene **16** in 97% yield and 100% enantiospecificity (Scheme 6). The exceptionally high yield in this reaction prompted us to explore the more challenging intramolecular Zweifel-type olefination of **13** as this would lead to a highly strained exomethylene cyclobutane. We were pleased to find that application of the same conditions to **13** gave **17** in 63% yield, again with complete selectivity (Scheme 6).

Deprotection of the methyl ether using NaSEt[13] gave 3-hydroxylaurene (**11**) and subsequent addition of catalytic amounts of TFA[14] led to clean cyclization to give debromofiliformin as a single diastereoisomer in 60% yield over two steps. Finally, bromination completed the synthesis of (−)-filiformin in a total of just nine steps, 98:2 d.r., and > 99:1 e.r. The analytical data was identical to that of the natural (−)-filiformin in all respects.[14]

In conclusion we have developed lithiation/borylation methodology for the construction of highly challenging quaternary-tertiary motifs in acyclic systems with full control of relative and absolute stereochemistry. Key to its success was the use of diamine-free lithiated carbamates to promote the addition step and allyl bromide to quench any benzylic carbanions formed during the 1,2-metallate rearrangement. A unique intramolecular Zweifel-type olefination enabled acyclic stereocontrol to be transformed into cyclic stereocontrol. These key steps were applied to the shortest enantioselective synthesis of (−)-filiformin (9 steps), the previous being 19 steps.[15]

Received: January 28, 2014
Published online: April 22, 2014

Keywords: boron · enantioselectivity · lithium · natural products · total synthesis

[1] For recent reviews on the asymmetric synthesis of quaternary stereocenters, see: a) A. Y. Hong, B. M. Stoltz, *Eur. J. Org. Chem.* **2013**, 2745; b) J. P. Das, I. Marek, *Chem. Commun.* **2011**, *47*, 4593; c) B. Wang, Y. Q. Tu, *Acc. Chem. Res.* **2011**, *44*, 1207; d) B. M. Trost, C. Jiang, *Synthesis* **2006**, 369; e) J. Christoffers, A. Baro, *Adv. Synth. Catal.* **2005**, *347*, 1473; f) *Quaternary Stereocenters: Challenges and Solutions for Organic Synthesis* (Eds.: J. Christoffers, A. Baro), VCH, Weinheim, **2005**; g) J. Christoffers, A. Mann, *Angew. Chem. Int. Ed.* **2001**, *40*, 4591; *Angew. Chem.* **2001**, *113*, 4725; For recent syntheses of natural products containing quaternary carbons with adjacent stereocenters, see: h) Z. Lu, Y. Li, J. Deng, A. Li, *Nat. Chem.* **2013**, *5*, 679; i) J. T. S. Yeoman, V. W. Mak, S. E. Reisman, *J. Am. Chem. Soc.* **2013**, *135*, 11764; j) M. Kawano, T. Kiuchi, S. Negishi, H. Tanaka, T. Hoshikawa, J. Matsuo, H. Ishibashi, *Angew. Chem. Int. Ed.* **2013**, *52*, 906; *Angew. Chem.* **2013**, *125*, 940; k) O. F. Jeker, A. G. Kravina, E. M. Carreira, *Angew. Chem. Int. Ed.* **2013**, *52*, 12166; *Angew. Chem.* **2013**, *125*, 12388; l) G. Valot, C. S. Regens, D. P. O'Malley, E. Godineau, H. Takikawa, A. Fürstner, *Angew. Chem. Int. Ed.* **2013**, *52*, 9534; *Angew. Chem.* **2013**, *125*, 9713.

[2] For reviews, see: a) H. K. Scott, V. K. Aggarwal, *Chem. Eur. J.* **2011**, *17*, 13124; b) S. P. Thomas, R. M. French, V. Jheengut, V. K. Aggarwal, *Chem. Rec.* **2009**, *9*, 24; For applications of the methodology, see: c) C. J. Fletcher, K. M. P. Wheelhouse, V. K. Aggarwal, *Angew. Chem. Int. Ed.* **2013**, *52*, 2503; *Angew. Chem.* **2013**, *125*, 2563; d) C. J. Fletcher, D. J. Blair, K. M. P. Wheelhouse, V. K. Aggarwal, *Tetrahedron* **2012**, *68*, 7598; e) G. Dutheuil, M. P. Webster, P. A. Worthington, V. K. Aggarwal, *Angew. Chem. Int. Ed.* **2009**, *48*, 6317; *Angew. Chem.* **2009**, *121*, 6435; For related reactions, see: f) X. Sun, P. R. Blakemore, *Org. Lett.* **2013**, *15*, 4500; g) P. R. Blakemore, M. S. Burge, *J. Am. Chem. Soc.* **2007**, *129*, 3068; h) P. R. Blakemore, S. P. Marsden, H. D. Vater, *Org. Lett.* **2006**, *8*, 4721; For a recent global review of Matteson's substrate controlled methodology, see: i) D. S. Matteson, *J. Org. Chem.* **2013**, *78*, 10009.

[3] a) V. Bagutski, R. M. French, V. K. Aggarwal, *Angew. Chem. Int. Ed.* **2010**, *49*, 5142; *Angew. Chem.* **2010**, *122*, 5268; b) J. L. Stymiest, V. Bagutski, R. M. French, V. K. Aggarwal, *Nature* **2008**, *456*, 778; c) A. Carstens, D. Hoppe, *Tetrahedron* **1994**, *50*, 6097; d) D. Hoppe, A. Carstens, T. Kramer, *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 1422; *Angew. Chem.* **1990**, *102*, 1455.

[4] a) J. L. Stymiest, G. Dutheuil, A. Mahmood, V. K. Aggarwal, *Angew. Chem. Int. Ed.* **2007**, *46*, 7491; *Angew. Chem.* **2007**, *119*, 7635; b) G. Besong, K. Jarowicki, P. J. Kocienski, E. Sliwinski, F. T. Boyle, *Org. Biomol. Chem.* **2006**, *4*, 2193; c) E. Beckmann, D. Hoppe, *Synthesis* **2005**, 217; d) E. Beckmann, V. Desai, D. Hoppe, *Synlett* **2004**, 2275; e) D. Hoppe, F. Hintze, P. Tebben, *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 1424; *Angew. Chem.* **1990**, *102*, 1457; For a review, see: f) D. Hoppe, F. Marr, M. Brüggemann in *Organolithiums in Enantioselective Synthesis*, *Vol. 5* (Ed.: D. M. Hodgson), Springer, London, **2003**, pp. 61–138.

[5] For intermolecular Zweifel olefinations, see: a) G. Zweifel, H. Arzoumanian, C. C. Whitney, *J. Am. Chem. Soc.* **1967**, *89*, 3652; b) D. A. Evans, T. C. Crawford, R. C. Thomas, J. A. Walker, *J. Org. Chem.* **1976**, *41*, 3947.

[6] Another strategy to reduce reversibility is to use a better leaving group in place of the carbamate, for example, 2,4,6-triisopropylbenzoates. See: R. Larouche-Gauthier, C. J. Fletcher, I. Couto, V. K. Aggarwal, *Chem. Commun.* **2011**, *47*, 12592. However, whilst successful in reducing reversibility and thereby increasing d.r., other problems arose: competing O-migration of the pinacol group and some over homologation was observed.

[7] CCDC 983768 (**5**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[8] a) A. J. Dixon, M. J. McGrath, P. O'Brien, *Org. Synth.* **2006**, *83*, 141; b) M. J. Dearden, C. R. Firkin, J-P. R. Hermet, P. O'Brien, *J. Am. Chem. Soc.* **2002**, *124*, 11870.

[9] D. Stead, G. Carbone, P. O'Brien, K. R. Campos, I. Coldham, A. Sanderson, *J. Am. Chem. Soc.* **2010**, *132*, 7260.

[10] The Cbx group, see: Ref. [3d]; D. Hoppe, P. Tebben, F. Hintze, T. Raffel (Bayer AG), US5223633, **1993**] was used in place of the Cb group as it gave crystalline intermediates. M. Binanzer, G. Y. Fang, V. K. Aggarwal, *Angew. Chem. Int. Ed.* **2010**, *49*, 4264; *Angew. Chem.* **2010**, *122*, 4360.

[11] P. Knochel, *J. Am. Chem. Soc.* **1990**, *112*, 7431.

[12] In addition to the boronic ester **12**, allylated **13** was also isolated in 27% yield (see the Supporting Information for details).

[13] S.-e. Yoo, J. H. Suh, K. Y. Yi, *Synthesis* **1998**, 771.

[14] R. Kazlauskas, P. T. Murphy, R. J. Quinn, R. J. Wells, *Aust. J. Chem.* **1976**, *29*, 2533.

[15] H. Nemoto, J. Miyata, H. Hakamata, M. Nagamochi, K. Fukumoto, *Tetrahedron* **1995**, *51*, 5511.

