Journal of Organometallic Chemistry 694 (2009) 3533–3541

Contents lists available at ScienceDirect

Journal of Organometallic Chemistry

journal homepage: www.elsevier.com/locate/jorganchem

Review

Benzoxaboroles – Old compounds with new applications

Agnieszka Adamczyk-Woźniak [a], Michał K. Cyrański [b], Anna Żubrowska [a], Andrzej Sporzyński [a,*]

[a] Faculty of Chemistry, Warsaw University of Technology, Noakowskiego 3, 00-664 Warsaw, Poland
[b] Faculty of Chemistry, University of Warsaw, Pasteura 1, 02-093 Warsaw, Poland

ARTICLE INFO

Article history:
Received 10 February 2009
Received in revised form 1 July 2009
Accepted 7 July 2009
Available online 12 July 2009

Keywords:
Boronic acids
Benzoxaboroles
Synthesis
Properties
Crystal structures
Applications

ABSTRACT

This comprehensive review covers the structure, methods of synthesis, properties and fields of application of benzoxaboroles – derivatives of phenylboronic acids. Some of the title compounds were described over 50 years ago, however most of them have been investigated only recently due to their exceptional properties and wide applications. In addition to their usage as building blocks and protecting groups in organic synthesis, certain benzoxaboroles display biological activity and are under clinical trials. They also bind hydroxyl compounds and thus can be applied as molecular receptors for sugars and glycoconjugates.

Contents

1. Introduction

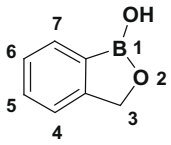
Boronic acids, $RB(OH)_2$, are objects of increasing interest due to their new applications in organic synthesis, catalysis, supramolecular chemistry, biology and medicine [1]. Following the research on molecular recognition, phenylboronic acids have also recently been employed as promising building blocks in crystal engineering in order to achieve predictably organized crystal materials [2]. Supramolecular assemblies of various types have been generated in this manner [3–5]. The reversibility of interactions between boronic acids and diols is widely applied in the construction of

* Corresponding author. Tel.: +48 22 2345737; fax: +48 22 6282741.
E-mail address: spor@ch.pw.edu.pl (A. Sporzyński).

0022-328X/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jorganchem.2009.07.022

molecular receptors [6] and makes them ideal candidates for the design of self-assembled molecular structures [7].

Only recently, great attention has been paid to the derivatives of phenylboronic acid – 1-hydroxy-1,3-dihydrobenzoxaboroles (**I**).



I

Benzoxaboroles were first synthesized and characterized as early as in 1957 [8]. They were found to have a very stable oxaborole ring and a high hydrolytic resistance of the boron–carbon bond in comparison with the corresponding boronic acids [9]. Moreover, they are usually better soluble in water than boronic acids.

After the discovery of the excellent antifungal activity of the 5-fluoro substituted benzoxaborole (AN2690) against onychomycosis [10,11], a systematic investigation of the medical applications of benzoxaboroles is being conducted [12]. Anti-inflammatory and antibacterial activity of substituted benzoxaboroles was recently reported [12]. Some of them are currently in preclinical and clinical trials.

The aim of this work is to review the described crystal structures of benzoxaboroles (**I**), their chemical properties, applications and methods of preparation.

There exists a large variety of common names of the described compounds. Early reports used such names as **boronophthalides** [9] or **arylboronolactones** [13]. Recently, names such as **benzoxaboroles** [10] or **benzoboroxoles** [14] are generally used.

Unsubstituted compound **I** (**1**, Supplementary Table S1) has the following systematic names:

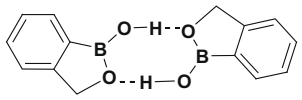
- 3*H*-benzo[c][1,2]oxaborol-1-ol or 2-oxa-1-bora-indan-1-ol (Beilstein),
- 3*H*-2,1-benzoxaborol-1-ol (CAS),
- 1-hydroxy-1,3-dihydro-benzo[c]-1,2-oxaborol (Houben-Weyl) [15].

Shortened names, e.g. 1,3-dihydro-1-hydroxy-2,1-benzoxaborole, are used in several papers and will be applied in this work.

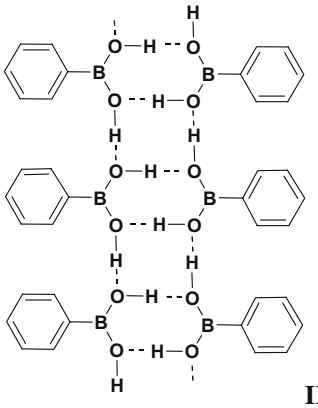
2. Crystal structure

Only a few crystal structures of benzoxaboroles are known up to date [16]. Similarly as in phenylboronic acids (**II**) the basic structural motive is a dimer with two intermolecular hydrogen bonds (**I**). Importantly, only one hydroxy group at the boron atom is present, and hence there is no possibility of lateral hydrogen bonds formation to form infinite 2D or 3D networks, as it is observed in the case of phenylboronic acids (**II**) [17]. The boron center is always trigonal (the sum of the angles at B is 360°), but unlike in phenylboronic acids, the BOO fragment is always coplanar with the phenyl fragment. Moreover, one of BO bonds is involved in a five-membered oxaborole ring and, as a consequence, a slight exaggeration in the distortion of the bond lengths and bond angles around the boron is observed. The exocyclic CBO angle is significantly bigger than the endocyclic one (the mean values 133.1° and 108.6°, respectively), whereas the exocyclic BO bond is shorter than the endocyclic one (the mean values 1.350 and 1.394 Å, respectively [18]). These geometric restraints appreciably reduce the diversity of possible types of crystal structures. Obviously, substitution at the phenyl ring and/or on the methylene carbon of oxaborole fragment can influence the molecular interactions both by steric and electronic effects, so more complicated patterns are also observed [19–21].

A closer inspection of the oxaborole fragment suggests that the electronic structure of the boron is extremely sensitive to the structural modifications arising from the substitution. This can be deduced from the ranges of geometric parameters: the exocyclic BO bond changes in the range 1.337(2) Å [22]–1.372(8) Å [14], whereas the endocyclic one changes in the range 1.372(2) Å [21]–1.412(8) Å [14]. Also the CB and CO bond lengths vary in wide ranges: from 1.496(10) Å [14] to 1.565(3) Å [23] and from 1.436(2) Å [22] to 1.488(2) Å [23], respectively. Importantly, these differences are not only the consequence of the electronic structure of the substituents, but also due to the intermolecular interactions in the crystal lattice [14,23].



I



II

The crystal lattice of unsubstituted benzoxaborole (1,3-dihydro-1-hydroxy-2,1-benzoxaborole (**1**)) consist of two independent molecules in an asymmetric part of the unit cell. The molecules form two kinds of planar centrosymmetric dimers, which are situated almost perpendicularly to each other (the angle between best planes calculated for all atoms of the dimers is 73.7°), see Fig. 1. [14]. The hydrogen bonds are rather strong and similar in both dimers (the O···O distances lie in the narrow range of 2.752(7)–2.725(2) Å), but the geometries of the benzoxaborole molecules differ significantly (the main differences are observed for the oxaborole fragment). For instance, the endocyclic BO or exocyclic BO(H) bond lengths differ by 0.046 Å or 0.021 Å, respectively. This is

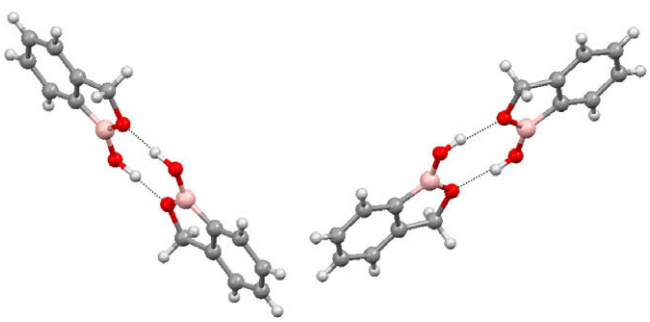


Fig. 1. The dimers formed by 1,3-dihydro-1-hydroxy-2,1-benzoxaborole (**1**).

somewhat surprising that such large discrepancies result from only a slightly different environment of Van der Waals interactions in the crystal lattice.

A similar structural motive is observed in the crystal structures of 1,3-dihydro-1-hydroxy-5,7-dimethoxy-2,1-benzoxaborole (**2**) [22] and 7-butyl-1,3-dihydro-1-hydroxy-5-methoxymethyl-2,1-benzoxaborole (**3**) [24] systems which are modified solely by substitution in the phenyl fragment (see Fig. 2). These molecules form one type of centrosymmetric dimer, where the interacting units are almost coplanar. The strengths of the hydrogen bonds are somewhat weaker compared with the unsubstituted system, but the difference is not large (the O···O distances in the range 2.764(1) Å (**3**)–2.790(2) Å (**2**)).

Substitution on the methylene carbon of oxaborole ring has much greater influence on the geometry of the system. The morpholinyl group (1,3-dihydro-1-hydroxy-3-(morpholin-4-yl)-2,1-benzoxaborole (**4**) Fig. 3), replacing one of the hydrogen atoms, does not change the centrosymmetric character of the hydrogen-bonded part, but moderately stratifies the parallel planes covering the interacting benzoxazole units (by ca. 0.5 Å) and increases the length of the hydrogen bonds (the O···O distance of 2.797(2) Å). This lengthening has been attributed to the steric effect of the morpholine fragment. The planes of morpholinyl groups are perpendicular to the planes of the central dimer ring, however, no other hydrogen bonds are observed with substituent atoms able to act as a hydrogen acceptor [23].

Introduction of the 2,6-dimethoxyphenyl group into oxaborole ring (1,3-dihydro-1-hydroxy-3-(2′,6′-dimethoxyphenyl)-2,1-benzoxaborole (**5**)) leads to the formation of a bifurcated hydrogen bond system in which an additional intramolecular hydrogen bond with one methoxy groups is formed [19] (Fig. 3). The structure is still centrosymmetric, however both hydrogen bond lengths are somewhat larger (the O···O distances are 3.027(1) and 2.928(1) Å, respectively, for the interaction between BO(H)···O (oxaborole ring) and BO(H)···O (methoxy group)), which is rather typical for bifurcated interactions. Again, the parallel planes covering the interacting benzoxaborole units are shifted to each other, but in this case the distance is much bigger than in other cases discussed before (equal to 1.667 Å).

Another type of intermolecular hydrogen bonds network has been found in the crystal structure of 1,3-dihydro-1,3-dihydroxy-4-formyl-2,1-benzoxaborole (**6**) (Fig. 4) [20]. In this case the hydroxy group at the methylene fragment effectively competes with the hydroxy group at the boron atom. The former group acts as a donor of hydrogen bond to an oxygen at the oxaborole ring (the distance O···O 2.825(1) Å), which leads to a nearly planar dimer. In turn, the hydroxy group at boron atom interacts with the formyl group at the phenyl fragment (the distance O···O 2.718(2) Å) and infinite chains of hydrogen-bonded dimers are formed in this way. Interestingly, this is not the only case when the hydroxy group at boron atom interacts with a partner other than the oxaborole ring. In 3-ethyl-1,3-dihydro-1-hydroxy-3-(4-hydroxybenzoyl)-2,1-benzoxaborole (**7**) [21], it serves as an acceptor of the intermolecular hydrogen bond where the donor is another hydroxy group from 4-hydroxybenzoyl substituent (the O···O distance 2.803(4) Å). This leads to a centrosymmetric dimer formation, where the benzoxaborole units lie in parallel planes shifted by 4.825 Å. On the other hand, the hydroxy group at boron atom serves also as a hydrogen bond donor to benzoyl oxygen atom being substituent in the neighboring molecule (O···O distance 2.722(3) Å), which leads to 3D structure where the neighboring oxaboroles are situated almost perpendicularly (they are twisted each other by 82.8°).

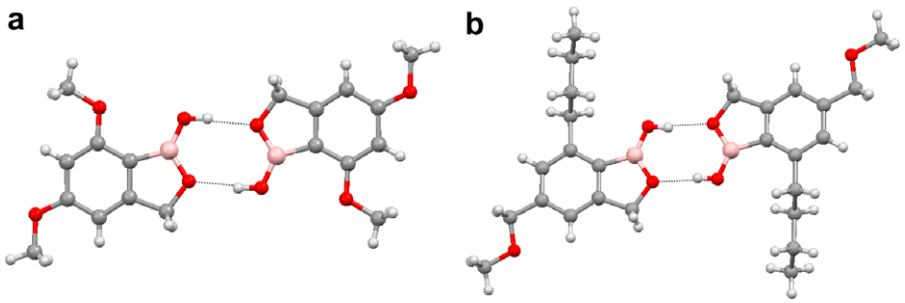


Fig. 2. The dimer formed by (a) 1,3-dihydro-1-hydroxy-5,7-dimethoxy-2,1-benzoxaborole (**2**) and (b) 7-butyl-1,3-dihydro-1-hydroxy-5-methoxymethyl-2,1-benzoxaborole (**3**).

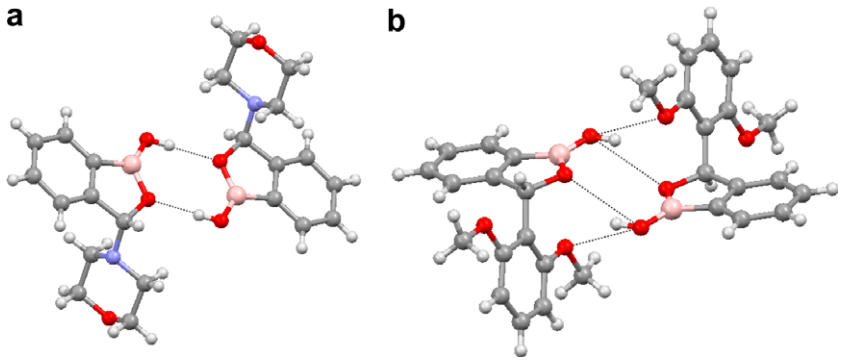


Fig. 3. The dimer formed by (a) 1,3-dihydro-1-hydroxy-3-(morpholin-4-yl)-2,1-benzoxaborole (**4**) and (b) 1,3-dihydro-1-hydroxy-3-(2′,6′-dimethoxyphenyl)-2,1-benzoxaborole (**5**).

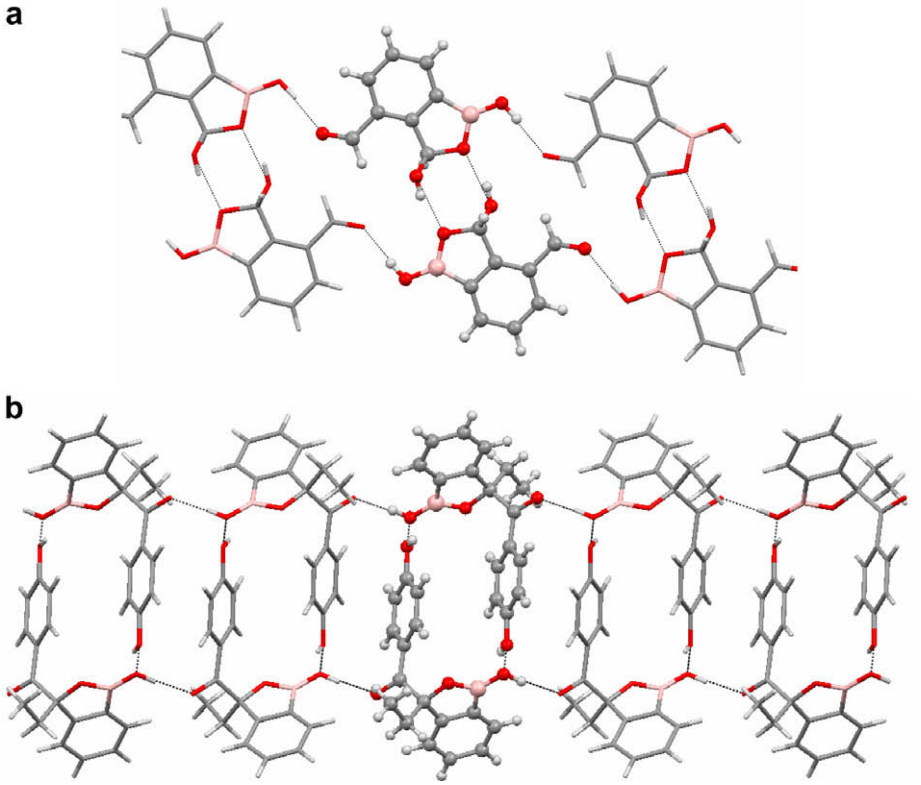


Fig. 4. The interactions in the crystal lattice of (a) 1,3-dihydro-1,3-dihydroxy-4-formyl-2,1-benzoxaborole (**6**) and (b) 3-ethyl-1,3-dihydro-1-hydroxy-3-(4-hydroxybenzoyl)-2,1-benzoxaborole (**7**). One of the dimeric units is distinguished by a ball and stick character.

3. Chemical behavior

Benzoxaboroles can be treated as internal esters of the corresponding *o*-hydroxymethylphenylboronic acids. In comparison with other esters of boronic acids, the stability of the ring B–O bond is very high [25]. It is completely resistant to hydrolysis: to the contrary, the corresponding *ortho*-hydroxymethylphenylboronic acid spontaneously dehydrates in water to form benzoxaboroles. Resistance to hydrolysis is also higher for B–C bond compared with boronic acid: benzoxaborole after 3 h refluxing with 10% HCl gives almost quantitatively an unreacted compound, while phenylboronic acid after 1.5 h decomposes in 90% [26].

The other piece of evidence of the high stability of the oxaborole ring is the formation of 1,3-dihydro-1,3-dihydroxybenzoxaboroles from the corresponding 2-formylphenylboronic acids [20,26,27]. It was suggested as early as in 1958 by Snyder et al. [26] and confirmed later by NMR and theoretical calculations [27]. The tautomeric equilibrium is shown in Scheme 8 . The equilibrium shift depends on the substituents in the phenyl ring. In the case of 3-hydroxy-4-formylbenzoxaborole, the cyclic form was isolated as a pure compound (structure shown in Fig. 4a) [20].

The reactivity of benzoxaboroles is similar to the corresponding boronic acids:

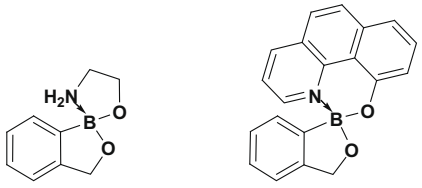
- Dehydration

Benzoxaboroles quantitatively form a linear anhydride on heating under vacuum [9,14] (Scheme 1).

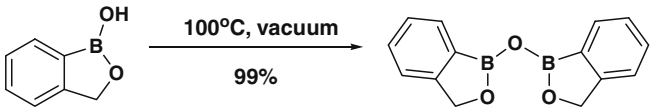
- Ester formation

Benzoxaboroles react with alcohols to form monoesters, which spontaneously hydrolyze on air [9] (Scheme 2).

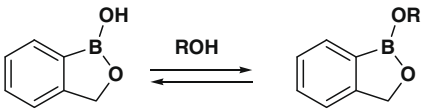
A more stable ester is formed with ethanolamine (**III**) due to the intramolecular complexation of boron by a nitrogen atom [25]. Another example of the intramolecular coordination is the ester of benzoxaborole with 10-hydroxybenzo[*h*]quinoline (**IV**) [28].



III **IV**



Scheme 1.



Scheme 2.

Formation of the cyclic esters by boronic acids with diols is the basis of boronic acids' action as sugar molecular receptors [6]. In that case cyclic esters are formed by both hydroxy groups in the boronic group. Similar cyclic esters can be formed by benzoxaboroles when the second hydroxy group is present in an anionic form of the benzoxaborole in neutral or slightly alkaline media [29] (Scheme 3).

The nature and selectivity of glycopyranosides binding was recently further discussed [30].

- Reactivity of B–OH bond

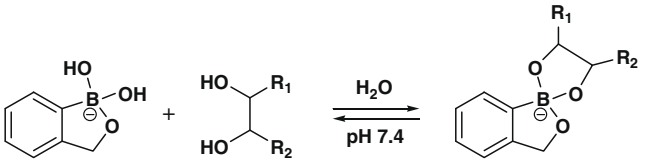
The nucleophilicity of the hydroxy group was found to be poor by studying the in situ preparation of chloro and alkyl substituted derivatives of benzoxaborole [14] (Scheme 4).

- Reactivity of B–C bond

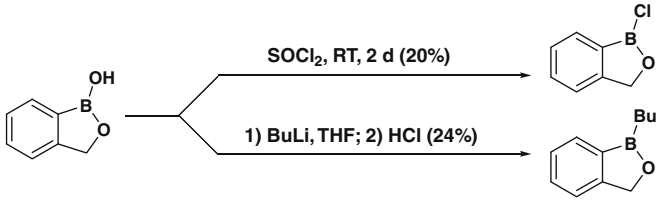
Benzoxaboroles [31] or their acetylated derivatives [24] were oxidized by hydrogen peroxide to form corresponding phenols (Scheme 5).

The title compounds react with aryl halides in Suzuki–Miyaura cross-coupling to form biaryls with hydroxymethyl group at *ortho* position [24,32] (Scheme 6).

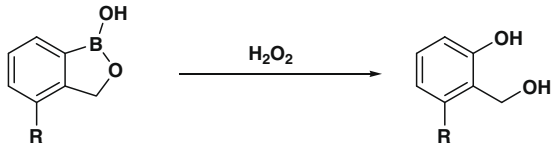
Other catalytic reactions with cleavage of B–C bond were also investigated [24] (Scheme 7).



Scheme 3.

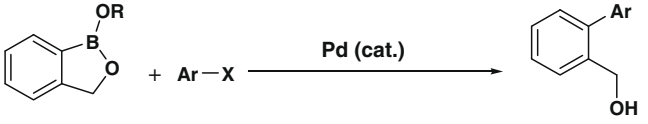


Scheme 4.



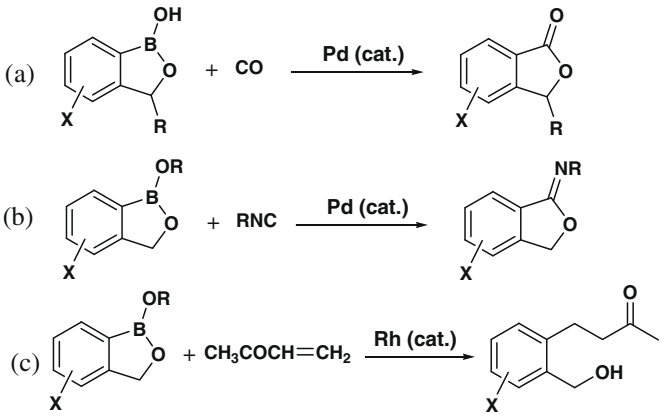
R = H (100%) or Br (64%)

Scheme 5.

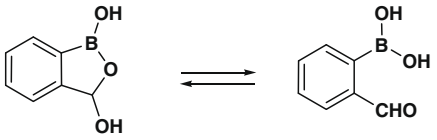


R = H or ^{i}Pr, X = Br or I

Scheme 6.



Scheme 7.



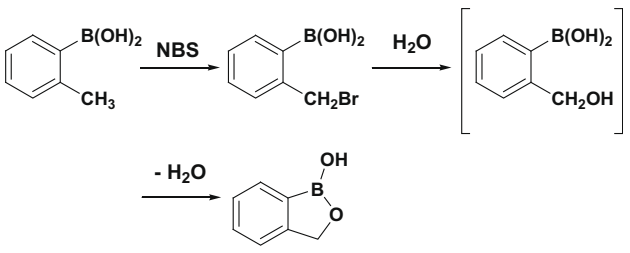
Scheme 8.

4. Synthesis

Benzoxaboroles are internal esters of the corresponding *ortho*-boronobenzyl alcohols. Such alcohols are unstable and their dehydration is so easy that it proceeds even during crystallization from water. Hence, the majority of synthetic methods is based on the introduction of a hydroxymethyl group to the boronic acid molecule (methods A) or a boronic group to benzyl alcohol (methods B). Depending on the particular systems, appropriate protection of the functional groups was necessary.

4.1. Methods A: functionalization of boronic acids and their derivatives

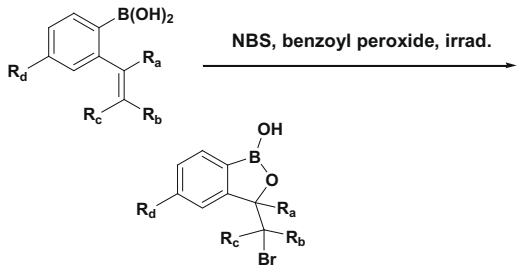
Unsubstituted benzoxaborole was obtained in a multistep synthesis from 2-methylphenylboronic acid, which was brominated by *N*-bromosuccinimide. The next step was the hydrolysis of the bromide to benzyl alcohol, which underwent intramolecular esterification [8,33,34] (method **A1**).



Method A1

The method can be modified by using corresponding benzyl iodide instead of bromide [21] (**A1a**). 3-Methyl-substituted benzoxaboroles were obtained similarly by using 2-ethylphenylboronic acid [35] (**A1b**).

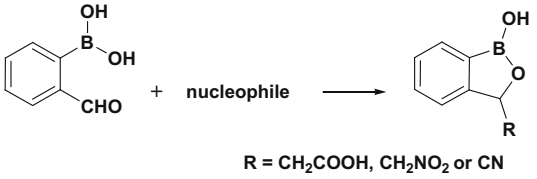
A modification of this method is bromination of the alkenyl substituted phenylboronic acid [13] (method **A2**).



Method A2

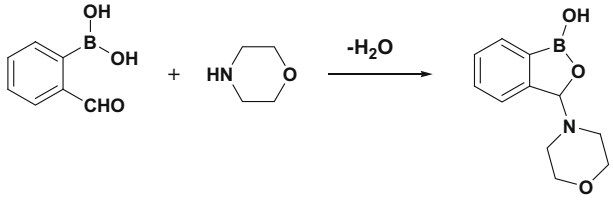
Bromine can be used instead of NBS [36] (**A2a**). In the methods described above, corresponding boroxins can be used instead of boronic acids [9,25,35].

3-Substituted benzoxaboroles can be obtained in the reaction of *o*-formylphenylboronic acid with nucleophiles [37] (method **A3**). The following compounds were used: malonic acid or isopropylidene malonate (**A3a**), nitromethane (**A3b**), or sodium cyanide (**A3c**), respectively.



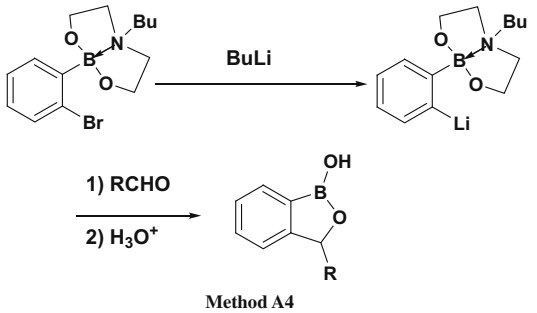
Method A3

Reaction with secondary amine leads to benzoxaboroles with amino group in position 3 [23] (**A3d**).



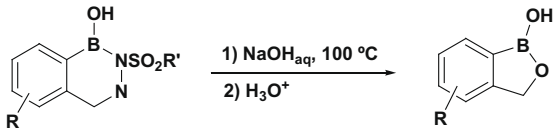
Method A3d

3-Substituted benzoxaboroles can be obtained in the reaction of organolithium compounds with an aldehyde. The boronic group should be protected as diethanolamine ester prior to lithiation [19] (**A4**).



Method A4

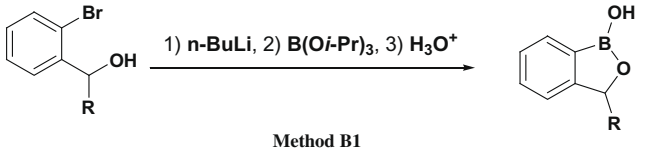
Alkaline hydrolysis of 1,2-dihydro-1-hydroxy-2,3,1-benzodiazaborines yields corresponding benzoxaboroles [31] (**A5**).



Method A5

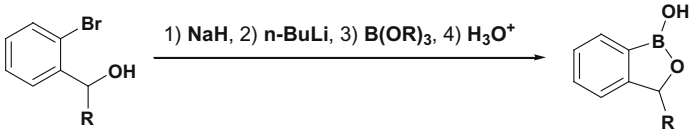
4.2. Methods B: introduction of boronic group into benzyl alcohol molecules

The most common substrates in this type of reaction were *ortho*-bromobenzyl alcohols, which reacted with butyllithium to give corresponding phenyllithium compounds [14,22,32]. The next steps were: reaction with trialkyl borate, hydrolysis and a subsequent spontaneous dehydration (method **B1**).



Method B1

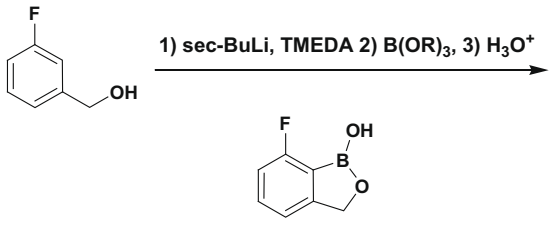
A modification of this method is the initial reaction of benzyl alcohol with one mole of sodium hydride, and further reactions as in method **B1** (method **B2**) [32].

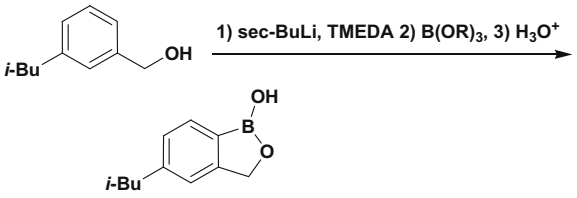


Method B2

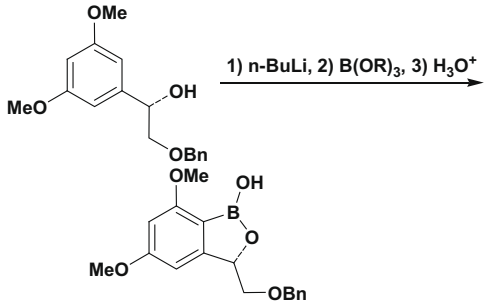
Alternatively, the hydroxyl group can be protected prior to the addition of butyllithium. Tetrahydropyranyl (THP) [22] or methoxymethyl (MOM) [10] groups were applied as the protecting group (methods **B2a** and **B2b**, respectively). *ortho*-Bromobenzyl alcohols used as substrates in these reactions can be obtained by the reduction of corresponding benzaldehydes or their reaction with Grignard reagents [32].

Several benzyl alcohols can be directly metalated with *sec*-butyllithium/TMEDA [10,38] or *n*-butyllithium [39] to give benzoxaboroles after reaction with borate, hydrolysis and cyclization (method **B3a**, **b**).



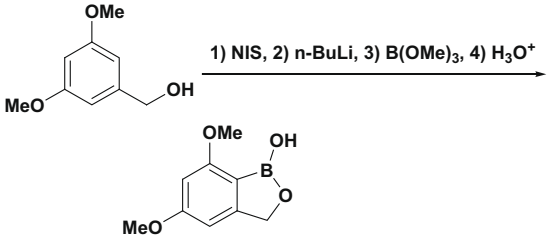


Method B3a



Method B3b

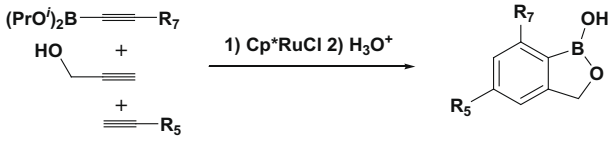
A modification of this method is the iodination as the first stage of the reactions sequence [40] (method **B4**).



Method B4

4.3. Method C: intermolecular catalytic cyclotrimerization

Benzoxaboroles can be obtained by catalytic cyclotrimerization of the appropriate alkynes [24].

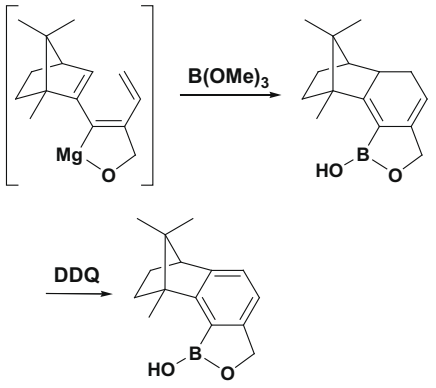


Method C

It is a convenient method for the synthesis of 5,7-disubstituted benzoxaboroles.

4.4. Method D

Benzoxaborole was obtained in the reaction of a corresponding magnesium compound with trimethoxyborate as a nucleophile and subsequent treatment with DDQ (dichlorodicyanoquinone) [41].



Method D

5. Applications

5.1. Organic synthesis

The most important synthetic application of benzoxaboroles is their use in Suzuki–Miyaura coupling (Scheme 6) [22,24,32,38–40,42–49]. In this reaction benzoxaboroles or their esters react with aryl halides to give *ortho*-arylsubstituted benzyl alcohols in high yield. In particular, 4,5-dimethoxy-substituted benzoxaborole was applied in the step of the synthesis of vancomycin [39,40,44,45,49]. Catalytic coupling with carbon monoxide and isocyanides gives lactones and cyclic imidates, respectively (Scheme 7a and b) [24]. Hayashi–Miyaura type catalytic coupling with methyl vinyl ketone leads to a keto substituted benzyl alcohol (Scheme 7c) [24].

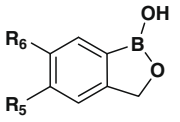
Another important application of benzoxaboroles in organic synthesis is their use as protecting groups. They are used for regioselective protection for selective glycosidation of sugars [50]. The compound with a methacrylic substituent was used to form polymerizable complexes with sterols. These imprinted polymers were used as protecting groups for regioselective acylations of trihydroxysteroids [51,52].

5.2. Molecular receptors

Unlike boronic acids, whose ability to bind polyols was widely investigated [6], benzoxaboroles were initially found to bind only monoalcohols [53]. It was not until more than twenty years later that they were found to be an improved class of sugar binding compounds [29]. The advantage of benzoxaboroles is their good solubility in water – they do not need any co-solvent for solubilization. They bind glycosides under physiologically relevant conditions. These compounds could be used in the design of oligomeric sensors for selective recognition of sugars, especially cell-surface glycoconjugates [29,30]. Sugar sensing in the NIR region, where there is minimal background signal from biomolecules in blood, was recently reported [54], which makes them a promising group of carbohydrate chemosensors. Benzoxaboroles were also used to detect carbohydrates by FT ion cyclotron MS technique [55]. The azo derivatives of benzoxaboroles were used as dyes for determination of polyols [56].

5.3. Medicine

5-Fluoro-1,3-dihydro-1-hydroxy-2,1-benzoxaborole, AN2690, is a broad-spectrum antifungal drug which easily transits through



AN2679, R_5=R_6=H,
AN2690, R_5=F, R_6=H,
AN2718, R_5=Cl, R_6=H,
AN2728, R_5=OC_6H_4-4-CN, R_6=H,
AN2898, R_5=OC_6H_3-3,4-CN, R_6=H,
AN3009, R_5=H, R_6=NHEt,
AN3018, R_5=F, R_6=NHEt.

Fig. 5. Biologically important benzoxaboroles.

the nail plate [57,58]. After the discovery of its antifungal properties [10,11,59], systematic investigations of biological activity of substituted benzoxaboroles were carried out [12,60]. Some general rules concerning their activity against *onychomycosis* were determined:

1. Five-membered ring containing boron is essential, carbon analogues are inactive.
2. Halo-substituents in the benzene ring increase activity.
3. Compounds with substituents in the position 5 reveal the highest activity.
4. Investigated compounds show MIC in the low μg/ml range.

Recently, 5-chloro-substituted benzoxaborole, AN2718, is being developed for the topical treatment of *tinea pedis* including the difficult to treat mocassin-type, which at present is only treatable with oral antifungals [12].

Benzoxaborole with cyanophenoxy substituents in the 5-position reveal anti-inflammatory activity against *psoriasis*, common skin disease, which is characterized by chronic inflammation. On the basis of structure–activity relationship studies, it was found that the 5-phenoxy group bearing an electron-withdrawing group at the para position was important for the activity, while the regioisomers of the cyano group were less active. Replacement of the cyano group retains the activity, but compounds with carboxy groups are less potent. The most active was the compound with 4-cyanophenoxy substituents (AN2728, in clinical trials [61]) and with a 3,4-dicyanophenoxy substituent (AN2898) [12].

Benzoxaboroxoles were also tested for the treatment of periodontal disease [62].

The structures of the most important biologically active benzoxaboroles are shown in Fig. 5.

5.4. Other applications

Numerous patents describe the use of benzoxaboroles in the fields discussed above. Additionally, they were used as biosensors for α-hydroxycarboxylic acids [63]. Their application as biocides for the protection of plastic materials, such as plasticized PVC [64], and for controlling and preventing the growth of microorganisms in aircraft fuel [65] were also described.

Acknowledgement

This work was supported by the Ministry of Science and Higher Education (Grant N204 01932/0614).

Appendix A. Supplementary data

Table S1 contains methods of synthesis, properties, reactivity and applications of benzoxaboroles, while in Table S2 selected molecular parameters of them are collected. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2009.07.022.

References

[1] D.G. Hall (Ed.), Boronic Acids: Preparation and Applications in Organic Synthesis and Medicine, Wiley-VCH, Weinheim, Germany, 2005.
[2] K.E. Maly, N. Malek, J.-H. Fournier, P. Rodriguez-Cuamatzi, T. Maris, J.D. Wuest, Pure Appl. Chem. 78 (2006) 1305.
[3] P. Rodriguez-Cuamatzi, G. Vargas-Diaz, H. Höpfl, Angew. Chem., Int. Ed. 43 (2004) 3041.
[4] P. Rogowska, M.K. Cyrański, A. Sporzyński, A. Ciesielski, Tetrahedron Lett. 47 (2006) 1389.
[5] M.R. Shimpi, N. SeethaLekshmi, V.R. Pedireddi, Cryst. Growth Des. 7 (2007) 1958.
[6] T.D. James, M.D. Phillips, S. Shinkai, Boronic Acids in Saccharide Recognition, Boronic Acids in Saccharide Recognition, Cambridge, UK, 2006.
[7] N. Fujita, S. Shinkai, T.D. James, Chem. Asian J. 3 (2008) 1076.
[8] K. Torssell, Ark. Kemi. 10 (1957) 507.
[9] R.R. Haynes, H.R. Snyder, J. Org. Chem. 29 (1964) 3229.
[10] S.J. Baker, Y.-K. Zhang, T. Akama, A. Lau, H. Zhou, V. Hernandez, W. Mao, M.R.K. Alley, V. Sanders, J.J. Plattner, J. Med. Chem. 49 (2006) 4447.
[11] F.L. Rock, W. Mao, A. Yaremchuk, M. Tukalo, T. Crepin, H. Zhou, Y.-K. Zhang, V. Hernandez, T. Akama, S.J. Baker, J.J. Plattner, L. Shapiro, S.A. Martinis, S.J. Benkovic, S. Cusack, M.R.K. Alley, Science 316 (2007) 1759.
[12] Anacor Pharmaceuticals, CA, USA, <http://www.anacor.com/conference_posters.php>.
[13] J.R. Falck, M. Bondlela, S.K. Venkataraman, D. Srinivas, J. Org. Chem. 66 (2001) 7148.
[14] V.V. Zhdankin, P.J. Persichini III, L. Zhang, S. Fix, P. Kiprof, Tetrahedron Lett. 40 (1999) 6705.
[15] Houben-Weyl, Methoden der Organischen Chemie, Organobor-Verbindungen III, vol. XII/3c, Georg Thieme Verlag, Stuttgart, Germany, 1984.
[16] Cambridge Structural Database, see: F.H. Allen, Acta Cryst. B 58 (2002) 380.
[17] M.K. Cyrański, A. Jezierska, P. Klimentowska, J.J. Panek, A. Sporzyński, J. Phys. Org. Chem. 21 (2008) 472.
[18] Based on geometries of benzoxaboroles discussed in this article.
[19] M. Dąbrowski, P. Kurach, S. Luliński, J. Serwatowski, Appl. Organometal. Chem. 21 (2007) 234.
[20] S. Luliński, J. Serwatowski, J. Organomet. Chem. 692 (2007) 2924.
[21] V.L. Arcus, L. Main, B.K. Nicholson, J. Organomet. Chem. 460 (1993) 139.
[22] Y.-L. Tan, A.J.P. White, D.A. Widdowson, R. Wilhelm, D.J. Williams, J. Chem. Soc., Perkin Trans. 1 (2001) 3269.
[23] A. Sporzyński, M. Lewandowski, P. Rogowska, M.K. Cyrański, Appl. Organometal. Chem. 19 (2005) 1202.
[24] Y. Yamamoto, J. Ishii, H. Nishiyama, K. Itoh, J. Am. Chem. Soc. 127 (2005) 9625.
[25] W.M.C. Cummings, C.H. Cox, H.R. Snyder, J. Org. Chem. 34 (1969) 1669.
[26] H.R. Snyder, A.J. Reedy, W.J. Lennarz, J. Am. Chem. Soc. 20 (1958) 835.
[27] S. Luliński, I. Madura, J. Serwatowski, H. Szatyłowicz, J. Zachara, New J. Chem. 31 (2007) 144.
[28] B. Robin, G. Buell, P. Kiprof, V.N. Nemykin, Acta Cryst. E 64 (2008) o314.
[29] M. Dowlut, D.G. Hall, J. Am. Chem. Soc. 128 (2006) 4226.
[30] M. Bérubé, M. Dowlut, D.G. Hall, J. Org. Chem. 73 (2008) 6471.
[31] M.A. Grassberger, Liebigs Ann. Chem. (1985) 683.
[32] D.S. Gunasekera, D.J. Gerold, N.S. Aalderks, J.S. Chandra, C.A. Maanu, P. Kiprof, V.V. Zhdankin, M.V.R. Reddy, Tetrahedron 63 (2007) 9401.
[33] R.T. Hawkins, W.J. Lennarz, H.R. Snyder, J. Am. Chem. Soc. 82 (1960) 3053.
[34] J. Lennarz, R. Snyder, J. Am. Chem. Soc. 82 (1960) 2172.
[35] W.J. Dale, J.R. Rush, J. Org. Chem. 27 (1962) 2598.
[36] N. Miyaura, A. Suzuki, J. Chem. Soc., Chem. Commun. (1979) 866.
[37] P. Tschampel, H.R. Snyder, J. Org. Chem. 29 (1964) 2168.
[38] N. Murugesan, Z. Gu, P.D. Stein, S. Bisaha, S. Spergel, R. Girotra, V.G. Lee, J. Lloyd, R.N. Misra, J. Schmidt, A. Mathur, L. Stratton, Y.F. Kelly, E. Bird, T. Waldron, E.C.-K. Liu, R. Zhang, H. Lee, R. Serafino, B. Abboa-Offei, P. Mathers, M. Giancarli, A.A. Seymour, M.L. Webb, S. Moreland, J.C. Barrish, J.T. Hunt, J. Med. Chem. 41 (1998) 5198.
[39] K.C. Nicolaou, S. Natarajan, H. Li, N.F. Jain, R. Hughes, M.E. Solomon, J.M. Ramanjulu, C.N.C. Boddy, M. Takayanagi, Angew. Chem., Int. Ed. 37 (1998) 2708.
[40] K.C. Nicolaou, J.M. Ramanjulu, S. Natarajan, S. Bräse, H. Li, C.N.C. Boddy, F. Rübsam, Chem. Commun. (1997) 1899.
[41] P.E. Tessier, N. Nguyen, M.D. Clay, A.G. Fallis, Org. Lett. 7 (2005) 767.
[42] A.G. Brown, M.J. Crimmin, P.D. Edwards, J. Chem. Soc., Perkin Trans. 1 (1992) 123.
[43] J.T. Link, B.K. Sorensen, J. Patel, M. Emery, M. Grynfarb, A. Goos-Nilsson, Bioorg. Med. Chem. Lett. 14 (2004) 2209.
[44] K.C. Nicolaou, H. Li, C.N.C. Boddy, J.M. Ramanjulu, T.-Y. Yue, S. Natarajan, X.-J. Chu, S. Bräse, F. Rübsam, Chem. Eur. J. 5 (1999) 2584.
[45] K.C. Nicolaou, A.E. Koumbis, M. Takayanagi, S. Natarajan, N.F. Jain, T. Bando, H. Li, R. Hughes, Chem. Eur. J. 5 (1999) 2622.
[46] Y. Yamamoto, J. Ishii, H. Nishiyama, K. Itoh, Tetrahedron 61 (2005) 11501.
[47] M. Prieto, S. Mayor, K. Rodriguez, P. Lloyd-Williams, E. Giralt, J. Org. Chem. 72 (2007) 1047.
[48] M. Gallant, M. Belley, M.-C. Carrière, A. Chateauneuf, D. Denis, N. Lachance, S. Lamontagne, K.M. Metters, N. Sawyer, D. Slipetz, J.F. Truchon, M. Labelle, Bioorg. Med. Chem. Lett. 13 (2003) 3813.
[49] K.C. Nicolaou, H. Li, C.N.C. Boddy, H. Li, A.E. Koumbis, R. Hughes, S. Natarajan, N.F. Jain, J.M. Ramanjulu, S. Bräse, M.E. Solomon, Chem. Eur. J. 5 (1999) 2602.

[50] K. Oshima, Y. Aoyama, J. Am. Chem. Soc. 121 (1999) 2315.
[51] C. Alexander, C.R. Smith, M.J. Whitcombe, E.N. Vulfson, J. Am. Chem. Soc. 121 (1999) 6640.
[52] O. Ramström, K. Mosbach, Curr. Opin. Chem. Biol. 3 (1999) 759.
[53] G. Wulff, Pure Appl. Chem. 54 (1982) 2093.
[54] Y. Kim, S.A. Hildebrand, R. Weissleder, C.-H. Tung, Chem. Commun. (2007) 2299.
[55] A. Ricardo, F. Frye, M.A. Carrigan, J.D. Tipton, D.H. Powell, S.A. Benner, J. Org. Chem. 71 (2006) 9503.
[56] A.P. Russell, C.W. Zepp, US Patent 5512246, 1996.
[57] X. Hui, S.J. Baker, R.C. Wester, S. Barbadillo, A.K. Cashmore, V. Sanders, K.M. Hold, T. Akama, Y-K. Zhang, J.J. Plattner, H.I. Maibach, J. Pharm. Sci. 96 (2007) 2622.
[58] S.J. Baker, X. Hui, H.I. Maibach, Ann. Rep. Med. Chem. 40 (2005) 323.
[59] M.R. Alley, S.J. Baker, K.R. Beutner, J. Plattner, Expert Opin. Inv. Drugs 16 (2007) 157.
[60] S.J. Baker, Y.-K. Zhang, T. Akama, C. Wheeler, J.J. Plattner, R.M. Rosser, R.P. Reid, N.S. Nixon, J. Labelled Compd. Rad. 50 (2007) 245.
[61] Anacor Pharmaceuticals, CA, USA, Expert Rev. Clin. Immunol. 4 (2008) 309.
[62] V. Sanders, K.R. Maples, J.J. Plattner, C. Bellinger-Kawahara, PCT Int. Appl. WO2007146965, 2007.
[63] C.R. Lowe, F.K. Sartain, X. Yang, PCT Int. Appl. WO2006079843, 2006.
[64] P.W. Austin, C.J. Kneale, P.J. Crowley, J.M. Clough, PCT Int. Appl. WO9533754, 1995.
[65] M. Singer, US Patent, 3873279, 1975.