Structures and Reactivities of Cocrystals Involving Diboronic Acids and Bipyridines: In Situ Linker Reaction and 1D-to-2D Dimensionality Change via Crystal-to-Crystal Photodimerization

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Abstract: Cocristallizations of diboronic acids [1,3-benzenedi
boronic acid (1,3-bdba), 1,4-benzenedicboronic acid (1,4-bdba)
and 4,4'-biphenyldiboronic acid (4,4'-bphdba)] and bipyri
dines [1,2-bis(4-pyridyl)ethylene (bpe) and 1,2-bis(4-
pyridyl)ethane (bpeta)] generated the hydrogen-bonded 1:2
cocrystals [(1,4-bdba)(bpe)] (1), [(1,4-bdba)(bpeta)] (2), [(1,3-
bdba)(bpe)][H2O] (3) and [(1,3-bdba)(bpeta)][H2O] (4),
wherein 1,3-bdba involved hydrated assemblies. The linear
extended 4,4'-bphdba exhibited the formation of 1:1 cocryst
als [(4,4'-bphdba)(bpe)] (5) and [(4,4'-bphdba-me)(bpeta)] (6).
For 6, a hemiester was generated by an in-situ linker trans
formation. Single-crystal X-ray diffraction revealed all
structures to be sustained by B(O)–H···N, B(O)–H···O, O–H···O,
O–H···N, C–H···O, C–H···π, and C–H···π interactions. The
cocrystals comprise 1D, 2D, and 3D hydrogen-bonded frame
works with components that display reactivities upon
cocrystal formation and within the solids. In 1 and 3, the C=C
bonds of the bpe molecules undergo a [2 + 2] photodimeriza
tion. UV radiation of each compound resulted in quantitative
conversion of bpe into cyclobutane tpcb. The reactivity
involving 1 occurred via 1D-to-2D single-crystal-to-single-
crystal (SCSC) transformation. Our work supports the feasi
bility of the diboronic acids as formidable structural and reactivity building blocks for cocrystal construction.

Introduction

Self-assembly is a ubiquitous process in Nature that enables systems to adapt to environmental changes.[1] At the molecular
level, adaptation originates from weak, non-covalent interac
tions and is subject to supramolecular synthons encoded in
molecular structures and the process of molecular
recognition.[2–7] In this context, boronic acids are highly versatile
building blocks to develop functional supramolecular materials
(for example, saccharide sensors,[8] pharmaceutics,[9–12] porous,[13]
and photoactive solids).[14,15] The acid moiety, for example, has a
capacity to accommodate conformational changes in the B(OH)2
group (that is, syn-syn, anti-syn, anti-anti) upon hydrogen-bond
mediated self-assembly.[16–18] The acid group also exhibits a
preference to function as a DD (where: D = hydrogen-bond
donor) module for molecular recognition with appropriate AA
moieties (where: A = hydrogen-bond acceptor).[19,20] Collectively,
the conformational flexibility and hydrogen-bonding capabil
ities allow for hydrogen-bonded substrates to be assembled
and organized in close proximity in the surrounding environ
ment of the acid.[21] While conformational landscapes of boronic
acids in the solid state are now becoming established,
information concerning the self-assembly of diboronic acids as
related to hydrogen-bond mediated self-assembly has yet to be
extensively addressed.[20]

In this context, reports by Bonifazi et al. exploit self-adap
ting abilities of diboronic acids to achieve supramolecular polymers[19] and discrete assemblies as DD units through H-bonding with AA N-acceptors.[20] The studies demon
strate diboronic acid recognition in the presence of comple
mentary acceptors. The work follows earlier studies by Pedir
eddi and Höpfl involving cocrystals of monoboronic and
diboronic acids with 4,4'-bipyridine (4,4'-bpy) and 1,2-bis(4-
pyridyl)ethylene (bpe).[22,23]

Given our recent studies involving cocrystals of monoboronic acids with N-acceptor bipyridines,[24,25] we sought to
explore the capacity of changes to the structures of diboronic acids [that is, 1,3-benzenedicboronic acid (1,3-bdba), 1,4-benze
nediboronic acid (1,4-bdba) and 4,4'-biphenyldiboronic acid

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(4,4'-bphdba) and bipyridine coformers [that is, alkane vs. alkene groups of bpe and 1,2-bis(4-pyridyl)ethane (bpeta)] to result in conformational and assembly variations of the B(OH)$_2$ groups. The variations are expected to trigger adaptability of boronic acids in the self-assembly process (Scheme 1).[22]

Our work involving cocrystals of boronic acids is also motivated by ongoing interests to direct photodimerizations in organic solids and, more generally, to learn how principles of supramolecular chemistry can affect and control chemical reactivity in the crystalline state. We identified monoboronic acids to function as hydrogen-bond-donor DD templates that direct intermolecular [2 + 2] photodimerizations of bpe to generate tpcb. After photoreaction, the resulting cyclobutane tpcb functions as an AA acceptor as evidenced by single-crystal reactivity properties.[14] Monoboronic acids can now be regarded as tools to control photocycloaddition in the solid state, although efforts are necessary to probe the scope of the self-assembly process and templating behavior. We have also demonstrated the ability of related boronic esters to serve as templates of monopyridines in the form of stilbazoles.[26]

Here, we report the self-assembly of diboronic acids and the extended bipyridines bpe and bpeta showing that subtle changes to constituent components lead to broad diversification of cocrystal composition, supramolecular architectures, crystalline motifs, and reactivities of components in both the solid state and liquid phase. We show linear 1,4-bdba to display all syn-syn and all anti-anti conformations in the 1:2 cocrystals [(1,4-bdba)(bpe)$_2$] (1) and [(1,4-bdba)(bpeta)$_2$] (2), respectively, generating 1D chains (Scheme 2a and b). For angular 1,3-bdba, the cocrystals exhibit hydrated 1:2:2 and 1:2:1 supramolecular assemblies[22] where the components of [(1,3-bdba)(bpe)$_2$]$_2$(H$_2$O)$_2$ (3) interact through all syn-syn conformations whereas in [(1,3-bdba)(bpeta)$_2$]$_2$(H$_2$O) (4) both syn-syn and syn-anti conformations are present (Scheme 2c and d). For linear extended 4,4'-bphdba, an all syn-anti conformation in the 1:1 cocrystal [(4,4'-bphdba)(bpe)] (5) supports a 1D polymer. For the saturated bipyridine, the extended diacid underwent an in-situ esterification with methanol upon cocrystallization to give [(4,4'-bphdba-me)(bpeta)] (6) as a 1D polymer with the diester in an all anti conformation (Scheme 2e and f). UV irradiation of both 1 and 3,[27] generates the cyclobutane derivative tpcb stereoselectively and in quantitative yield. For 1, the reaction in the solid state occurs in a single-crystal-to-single-crystal (SCSC) transformation wherein the dimensionality of the polymer undergoes a 1D-to-2D change to generate [(1,4-bdba)(tpcb)] (1R). In the photo-reacted solid, the photoproduct tpcb interacts with four different diboronic acids.

![Scheme 1. Diboronic acids and bipyridine coformers studied.](attachment://image.png)
Scheme 2. Hydrogen-bonded architectures involving diboronic acids (1,3-bdba, 1,4-bdba and 4,4'-bphdba) and bipyridines (bpeta and bpe).

Scheme 3. Transformation of 4,4'-bphdba to the hemiester-based cocrystal 6. Reaction involves partial replacement of (B)OH by –OMe and loss of water.
Results and Discussion

Our original aim was to compare structural hydrogen-bonding motifs containing diboronic acids (1,3-bdba, 1,4-bdba and 4,4'-bphdba) and bipyridines (bpeta and bpe). The ditopic hydrogen-bond-acceptors were selected based on structural effects that arise owing to the different hybridizations of the central carbon-carbon linkage (sp³ vs. sp²). To synthesize the cocrystals, the corresponding diboronic acid was placed in a vial with methanol and acetone as solvents. Each bipyridine was then added in a 1:2 stoichiometry and the solution stirred for approximately 10 min at room temperature. Crystals suitable for single-crystal X-ray diffraction (SCXRD) analysis were achieved by slow solvent evaporation (Figures S1–S7, see Supporting Information). Relevant crystallographic data are summarized in Tables S1–S7. Phase purities were established by comparisons of calculated and experimental powder X-ray diffraction analysis (PXRD) patterns (Figures S8–S13, see Supporting Information).

Single-crystal X-ray diffraction analyses

Assemblies of 1,4-bdba and single-crystal reactivity with bpe

Cocrystallizations of the linear diacid 1,4-bdba with bpe and bpeta afforded \([(1,4-bdba)(bpe)_2]\) (1) and \([(1,4-bdba)(bpeta)_2]\) (2), respectively. The components of 1 crystallize in the monoclinic space group \(\text{C}2/\text{m}\), with the asymmetric unit consisting of a quarter molecule of 1,4-bdba and a half molecule of bpe (Figure S1, see Supporting Information) to give a 1D supramolecular arrangement sustained by \(\text{B(O)}-\text{H}--\text{N}_{\text{pyr}}\) hydrogen bonds [O···N, 2.735(14) Å/2.860(12) Å; \(\text{O}--\text{N} 155°/152°\)]. The diacid adopts the \(\text{all syn-syn}\) conformation such that
the bpe molecules assemble as face-to-face π-stacked dimers within the 1D structure [centroid-centroid 3.59 Å and N···N 3.527(4) Å]. The conformation is akin to a DD hydrogen-bond donor module. The B(OH)_2 groups lie coplanar (0.08°) with the pendant aromatic ring while the bpe and 1,4-bdba rings are twisted toward orthogonal (64°). The pyridyl rings of bpe are approximately coplanar (twist angle ~5.73°). The stacking of bpe generates infinite face-to-face π stacks with the combined hydrogen bonding and stacking producing a 2D arrangement within the bc-plane (Figure 1a). The C=C bonds of bpe lie disordered over two sites (occupancies: 0.45/0.55 at temperature 298 K). The stacked alkenes are parallel with the C=C bonds separated by 3.80 Å and 3.91 Å, which is a geometry suitable for an intermolecular [2 + 2] photodimerization.

Figure 2. X-ray structure of 2: a) 1D strands based on (B)O-H···Npyr and C-H-π interactions, b) 2D hydrogen bonded framework in ac-plane, and c) 3D network through additional C-H-π contacts. Symmetry operators: i) 1 + x, 1 + y, 1 + z; ii) x, 1 + y, 1 + z; iii) –x, 1 + y, 1 – z.
When single crystals of 1 were subjected to UV irradiation for 3 h (450 W, medium-pressure Hg-lamp), bpe reacted to form \([1,4\text{-bd}ba](\text{tpcb})\) (1R) in quantitative yield as confirmed by \(^1\text{H}\) NMR spectroscopy (Figure S21; see Supporting Information). The formation of tpcb was evidenced by the disappearance of the olefinic signals (7.54 ppm) and appearance of cyclobutane signals (4.66 ppm). Visual examination suggested the single crystals to undergo a SCSC photoreaction.

A SCXRD analysis of the photoreacted solid 1R revealed components of the cocrystal to undergo a SCSC transformation. The components occupy the same monoclinic space group C2/m, with the asymmetric unit consisting of a quarter molecule of 1,4-bdba and a quarter molecule of tpcb. The cyclobutane lies disordered on a two-fold rotation axis (occupancies: 0.45/0.55) (Figure S2, see Supporting Information). The cell volume of 1R increased on the order of 1.6% versus the unreacted solid.

The SCSC transformation, thus, involved a 1D-to-2D change in dimensionality of the hydrogen bonds. To our knowledge, 1R is the first example of a hydrogen-bonded architecture based on a diboronic acid that undergoes a change in dimensionality. There is, thus, a need to consider changes in dimensionality that can occur when engineering topochemically reactive alkenes in solids based on the \(-\text{B(OH)}_2\) group. The observations also attest to the conformational flexibility of the \(-\text{B(OH)}_2\) group.

The components of 2 crystallize in the triclinic space group P-1 with one molecule of bpeta and half of 1,4-bdba in the asymmetric unit (Figure S3, see Supporting Information). In contrast to 1, the diboronic acid adopts an all anti-anti conformation and the long molecular axes of 1,4-bdba and the coformer are oriented perpendicular to each other, instead of parallel. Similar to 1, the components form a 1D supramolecular arrangement in the ac-plane sustained by \(\text{B(O)}-\text{H} \cdots \text{N}_{\text{bp}}\) [O–N 2.742(15) Å/2.778(15) Å; \(-\text{O} \cdots \text{N} 165°/156°; \text{N}–\text{N} 3.308(3) \text{ Å} \)], Owing to the photoreaction, the components participate in a 2D hydrogen-bonded polymer in the bc-plane. The SCSC transformation, thus, involved a 1D-to-2D change in dimensionality of the hydrogen bonds. To our knowledge, 1R is the first example of a hydrogen-bonded architecture based on a diboronic acid that undergoes a change in dimensionality. There is, thus, a need to consider changes in dimensionality that can occur when engineering topochemically reactive alkenes in solids based on the \(-\text{B(OH)}_2\) group. The observations also attest to the conformational flexibility of the \(-\text{B(OH)}_2\) group.
The B(OH)$_2$ groups are twisted out-of-plane of the aromatic ring (O1–B1–C1–C3, $29.2(2)\degree$; O1–B1–C1–C2, $150.05(15)\degree$). The resulting 2D framework is further stabilized by weaker C–H···O(B) (C···O, 3.223(2) Å; C···O(B), 133\degree) interactions (Figure 2b). The layers interact by C–H···π (C···π 2.89 Å) interactions among 1,4-bdba and bpeta, which drives the formation of a 3D supramolecular network (Figure 2c).

Assemblies of 1,3-bdba and water-assisted hydrogen-bonding

The solid-state structures of [(1,3-bdba)(bpe)$_2$(H$_2$O)$_2$] (3) and [(1,3-bdba)(bpeta)$_2$(H$_2$O)] (4) involve the generation of supramolecular catenemers, in which included water molecules extend the hydrogen-bonding motifs. The role of water to organize molecules in cocrystals of diboronic acids has been identified first experimentally, with a theoretical treatment suggesting significant binding energies. The components of 3 crystallize in the monoclinic space group C2/c. The asymmetric unit consists of one molecule of...
bpe, a half molecule of 1,3-bdba and one molecule of water (Figure S4, see Supporting Information), indicating a 1 : 2 : 2 stoichiometry. A single B(OH) group participates in a (B)O–H···N<sub>pyr</sub> [O···N, 2.676(4) Å; ff O–H···N, 152°] hydrogen bond. Inclusion of the water results in a highly organized 2D framework sustained by O<sub>w</sub>–H···N<sub>pyr</sub> [O···N, 2.831(4) Å; ff O–H···N, 169°] and (B)O–H···O<sub>w</sub>/O<sub>w</sub>–H···O(B) [O···O, 2.793(4) Å; ff O–H···O, 144/171°] hydrogen bonds. The packing is isostructural to the hydrogen-bonded analog [(1,3-bdba)(bpy)<sub>2</sub>(H<sub>2</sub>O)<sub>2</sub>]<sup>[22]</sup>. The acid adopts an all syn-syn conformation with the B(OH)<sub>2</sub> groups approximately coplanar with the aromatic ring (distortion angle: −3.2(5)° for C<sub>2</sub> – C<sub>1</sub> – B<sub>1</sub> – O<sub>1</sub>). The pyridyl rings of bpe deviate from coplanarity (twist angle −9.8°). As a consequence of the assembly, the bpe molecules form infinite face-to-face π–π stacks with nearest-neighbor C–C bonds separated on the order of 3.67 Å, which satisfies the geometry criteria for a [2 + 2] photodimerization<sup>[23]</sup> (Figure 3a and b). When irradiated with UV-radiation, the cocrystal 3 was determined to be photoactive to generate tpcb in quantitative yield (Figure S22; see Supporting Information). We note that after the photoreaction, the PXRD diffractogram exhibited significant broadening (Figure S14; see Supporting Information) excluding a SCSC transformation in this case.

The components of 4 crystallize in the triclinic space group P-1 with one 1,3-bdba, two bpeta, and a water molecule in the asymmetric unit (Figure S5, see Supporting Information) yielding now a 1 : 2 : 1 composition. The (B)OH groups interact with three bpeta molecules by three (B)O–H···N<sub>pyr</sub> [O···N, 2.743(2) Å; ff O–H···N, 160°] and (B)O–H···O<sub>1</sub>/O<sub>1</sub>–H···O(B) [O···O, 2.771(2) Å; ff O–H···O, 160°] hydrogen bonds. In the arrangement, one of the acid groups serves as a DD hydrogen-bond donor module. The remaining (B)OH group participates in (B)O–H···O<sub>2</sub> [O···O, 2.747(1) Å/2.845(2) Å; ff O–H···O, 145°/156°/156°] hydrogen bonds. In the arrangement, one of the acid groups serves as a DD hydrogen-bond donor module. The remaining (B)OH group participates in both (B)O–H···O<sub>1</sub> [O···O, 2.721(2) Å; ff O–H···O, 169°] and O<sub>1</sub>–H···O(B) [O···O, 2.771(2) Å; ff O–H···O, 160°] hydrogen bonds with the included water (Figure 4a). The water
Figure 6. X-ray structure of 6: a) 1D motif formed by (B)O–H···N<sub>pyr</sub> hydrogen bonds, b) 2D hydrogen bonded framework in the bc-plane, c) C–H···π contacts between the 4,4'-bphdba and bpeta along c. Symmetry operators: i) 1 − x, 2 − y, − z; ii) − x, 1 − y, 1 − z.
molecule also interacts with the bipyridine by \(O\_v-H-N\_pyr\) (O–N, 2.844(2) Å; \(O-H-N, 1.64\)) hydrogen bonds. The acid exhibits both syn-syn and syn-anti conformations. The B(OH)\(_2\) groups in 1,3-bdba are approximately planar to the aromatic ring (torsion angles: \(-2.5(2)\)^\circ\) to \(-4.3(2)\)^\circ\) while the pyridyl groups of the two bipyridines are significantly twisted (torsion angles: 46° and 88°). The components assemble to generate a 2D structure stabilized by C–H–N\_pyr and C–H–O contacts within the ab-plane, with the bpe molecules engaged in edge-to-face π–π (3.91 Å) and C–H–π (2.72–2.94 Å) interactions (Figure 4b).

Assemblies of 4,4′-bphdba and in-situ linker reaction

The solid-state structures of [(4,4′-bphdba)(bpe)] (5) and [(4,4′-bphba-me)(bpeta)] (6) involve, similar to 1 and 2, the generation of 1D hydrogen-bonded arrays sustained by B(OH)\(_2\)–H–N\_pyr hydrogen bonds. For 5, the acid conformation results in a 2D hydrogen-bonded framework. For 6, an in-situ linker reaction with methanol to generate a hemiester effectively restricts the self-assembly process to a single dimension.

The components of 5 assemble in the triclinic space group P-1. The asymmetric unit contains two halves each of 4,4′-bphdba and bpe molecules (Figure S6, see Supporting Information) that interact by B(O)–H–N\_pyr hydrogen bonds. For 5, the acid conformation results in a 2D hydrogen-bonded framework. For 6, an in-situ linker reaction with methanol to generate a hemiester effectively restricts the dimensionality of the self-assembly process relative to 5. We note that in-situ linker transformations are reported for metal–organic frameworks (i.e., MOFs) and materials. The one-pot reactions have been shown to be useful to generate unusual organic ligands that are a challenge to access in the generation of novel MOF materials. In the current study, the in-situ formation of the hemiester may provide a unique avenue to construct novel organic cocrystals based on diboronic acids.

Conclusion

We have reported a comparison of structural and reactivity aspects concerning cocrystals and hydrogen-bonded frameworks involving diboronic acids and bipyridines. The comparative analysis reveals that the cocrystals with the diboronic acids play an important role to support adaptability of the diboronic acids in the self-assembly process. UV radiation of single crystals of 1 resulted in the 1D-to-2D crystal-to-crystal [2 + 2] photodimerization. Our work also shows the formation of hemiester 6 by in-situ linker transformation. We expect our results to impact the further development of polymeric assemblies based on boronic acids in organic solids and as related to field of crystal engineering.

Deposition Number(s) 2121702 (for 1), 2121707 (for 1R), 2121704 (for 2), 2121706 (for 3), 2121705 (for 4), 2121703 (for 5), 2121701 (for 6) contain(s) the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: [2 + 2] photodimerization · bipyridines · cocystals · diboron acids · in situ linker transformation

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