Polyhydroxyoligothiophenes. 2. Hydrogen-Bonding-Oriented Solid State Conformation of 3,3′-Bis(2-hydroxyethyl)-2,2′-bithiophene and Regioselective Synthesis of the Corresponding Head-to-Head/Tail-to-Tail Quater- and Sexithiophene

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This paper reports the X-ray structure of 3,3′-bis(2-hydroxyethyl)-2,2′-bithiophene (**1**), which is the building block for the synthesis of head-to-head/tail-to-tail 2-hydroxyethyl-substituted oligothiophenes. Contrary to all the bithiophenes reported so far, **1** exhibits a noncoplanar *anti* conformation and an inter-ring twist angle (67.5°) which is the largest ever measured for adjacent rings of α-conjugated oligothiophenes. This unusual conformation appears to be dictated by intermolecular hydrogen-bonding interactions involving the OH groups, which bind the molecule in close packed layers. The paper also describes the regioselective synthesis of the dimer and the trimer of **1**, namely of 3,3′,4″,3‴-tetrakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴-quaterthiophene (**3c**) and of 3,3′,4″,3‴,4⁗,3⁗′-hexakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴:5‴,2⁗:5⁗,2⁗′-sexithiophene (**4b**). **3c** And **4b** were obtained through palladium(0)-catalyzed coupling of the mono- and distannanes of the tetrahydropyranyl derivative of **1** with the appropriate monobromo compound (Stille's reaction). Finally, the paper reports force-field calculations which suggest that the low λ_{max} values measured for **1**, **3c**, and **4b** are also the result of intramolecular hydrogen-bonding interactions which favor highly twisted conformations in solution.

Functionalized α-conjugated oligo- and polythiophenes are a matter of large current interest because of their numerous properties (electric conductivity, electroluminescence, electro-, termo-, and solvatochromism, etc.) and the variety of functional side groups which can be linked to the aromatic skeleton to enhance and control these properties.[1] Functionalization with hydrophilic groups renders these materials soluble in water and opens the way to their use as optical transducers in biosensors.[2] In general, regioregular polythiophenes display better properties than those of the corresponding regiorandom materials.[3]

Obtaining ordered molecular organization in solid—either in monocrystals or in thin films—is one of the main objectives of research in the field of oligo and polythiophenes since order leads to better electric and electrooptical properties.[4] It has been recently shown that highly ordered thin films of α-conjugated sexithiophene display field-induced conductivities and field-effect mobilities which are among the best measured for organic solids and are good enough to envisage practical applications of sexithiophene-based thin film transistors in large-area electronic circuits.[5]

We have recently started a research work aimed at synthesizing regioregular polyhydroxyoligothiophenes.[6] Our interest in these compounds was due, on one hand, to their being precursors for the preparation of water soluble oligo(3-thienylalkanesulfonates)[2a,b] and, on the other, to the fact that functionalization with alkyl chains terminating with hydroxyl groups might be a way to tailor the solid state organization of these materials through inter- and intramolecular hydrogen bonding interactions.

In the literature there are numerous examples of self-assembly in supramolecular structures based on molecular recognition by hydrogen bonding (see, for example, reference 7) but, as far as we are aware, very little has been reported related to the problem of the solid state organization of oligo and polythiophenes. Thus, we have undertaken an exploratory work aimed at: (1) checking whether β-functionalization with groups capable of H-bonding confers unusual properties to bithiophene derivatives in solid; (2) developing a strategy for the regioselective synthesis and the spectroscopic characterization of longer oligothiophenes of the same type.

We report herein the single-crystal X-ray structure of 3,3′-(2-hydroxyethyl)-2,2′-bithiophene, **1**,[6] which shows that intermolecular H-bonding locks the molecule in a

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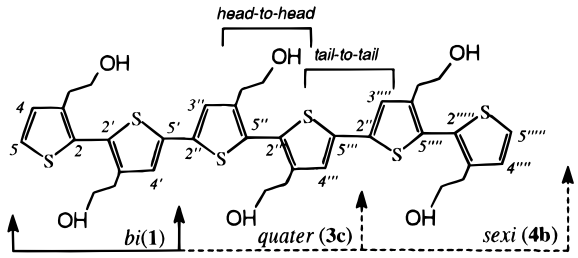
Scheme 1. Structure and Numbering of Head-to-Head 3,3′-Bis(2-hydroxyethyl)-2,2′-bithiophene (1) and of the Corresponding Quater- (3c) and Sexithiophene (4b)



largely twisted conformation which has never been observed for any of the bithiophenes reported so far and also leads to a very unusual packing arrangement for these kinds of compounds. Furthermore we show that the dimer and the trimer of **1**, namely 3,3′,4″,3‴-tetrakis-(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴-quaterthiophene (**3c**) and 3,3′,4″,3‴,4⁗,3⁗′-hexakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴:5‴,2⁗:5⁗,2⁗′:5⁗′,2′⁗′-sexithiophene (**4b**)—whose structures and numbering schemes are given in Scheme 1—can be prepared *via* Stille's reaction, *i.e.* palladium(0)-catalyzed coupling of the appropriate stannyl and bromo derivatives.[8]

Finally, we report some results of MM3 force field calculations showing the importance of intramolecular H-bonds on the conformational preferences of the substrates.

Results

1. X-ray Structure Analysis of 3,3′-Bis(2-hydroxyethyl)-2,2′-bithiophene (1).[29] The X-ray structure of **1**[6] is shown in Figure 1, along with bond distances and angles, while Figure 2 gives the stereoview of the crystal packing.

The molecule has precise, *i.e.* crystallographically dictated, 2-fold rotational symmetry. The thiophene rings display a noncoplanar *anti* conformation, characterized by a S−C(2)−C(2′)−S′ torsional angle of 110.8(5)°, whereas the dihedral angle between mean planes through the five-membered rings is 67.5(1)°. The inter-ring C−C bond distance [1.481(7) Å] is longer (about 0.03 Å) than those observed in coplanar or less twisted thiophene oligomers.[9−18,21] The dimensions of the thiophene ring, whose atoms are coplanar within ±0.004(3) Å, appear to be

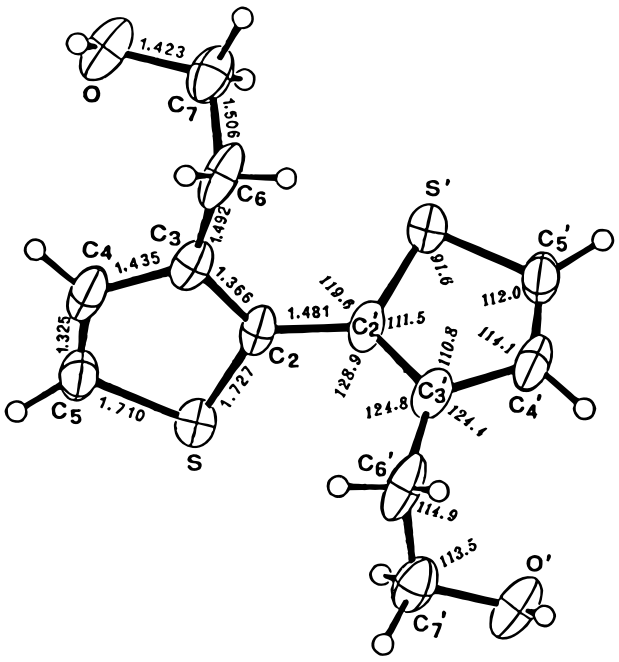


Figure 1. ORTEP drawing of 3,3′-bis(2-hydroxyethyl)-2,2′-bithiophene (**1**) showing the atom numbering, bond distances (Å), and bond angles (deg). Thermal ellipsoids for non-H atoms enclose 40% probability. Primed atoms are related to unprimed by a two-fold axis through the midpoint of the C(2)−C(2′) bond.

scarcely affected by the loss of π-conjugation between rings, due to their twisting. Only the C(4)−C(5) bond distance is somewhat shorter than those reported in the literature,[9−18,21] but is consistent with that of 1.327(7) Å found in 3,3′-dimethoxy-2,2′-bithiophene,[11] and with those observed in the external rings of some quaterthiophene derivatives.[12b,c,14] Each OH function is involved in two (symmetry related) intermolecular hydrogen bonding contacts, where the O atom acts either as a proton donor or acceptor. The O···O and H···O separations are 2.705-(3) and 1.99 Å, respectively, and the subtended O−H···O angle 174°. Thus, each molecule is hydrogen-bonded to four glide-plane-related molecules, these latter being stacked along the b or c cell axis. The resulting layered structure, parallel to the bc plane, is completely different from those previously reported for other planar or like-planar oligothiophenes, for which a "herringbone" packing motif is always the preferred one.[13] None of the intermolecular distances (inter- or intralayer) is shorter than those expected for the conventional van der Waals contacts. It is of interest to note that this occurs, with only one exception,[12d] in the crystal packing of all thiophene oligomers of which we are aware. Furthermore the shortest S···S contact, a parameter of great importance from the point of view of the crystal conduction properties, is in this case 4.033(2) Å.

2. Synthesis and Spectroscopic Characterization of 3,3′,4″,3‴-Tetrakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴-quaterthiophene (3c) and 3,3′,4″,3‴,4⁗,3⁗′-Hexakis-(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴:5‴,2⁗:5⁗,2⁗′:5⁗′,2′⁗′-sexithiophene (4b). Scheme 2 gives the synthetic pattern followed to obtain compounds **3c** and **4b** *via* Stille's reaction.[8]

The starting building block, **2**, was obtained in good yield by palladium(0)-catalyzed coupling of 2-bromo-3-[2-(tetrahydropyranyloxy)ethyl]thiophene with 2-(tributylstannyl)-3-[2-(tetrahydropyranyloxy)ethyl]thio-

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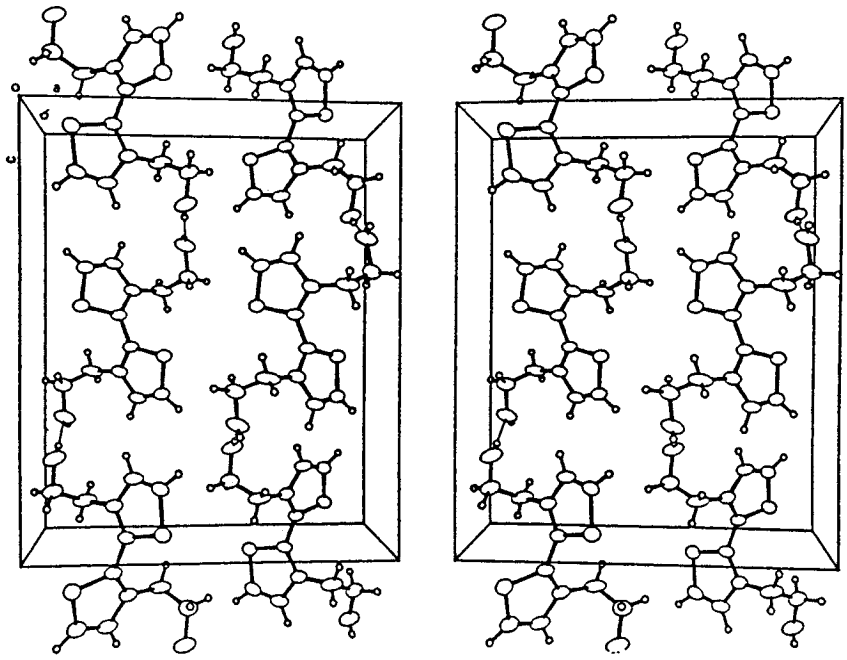
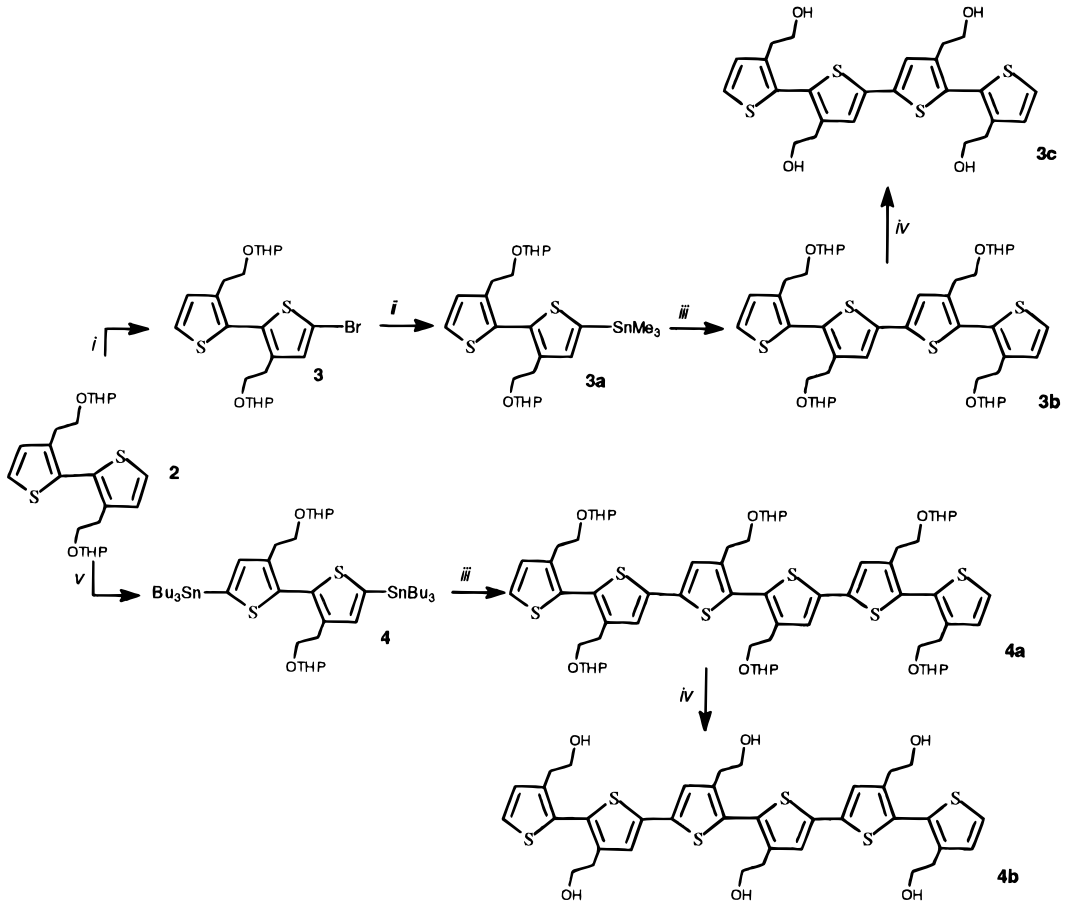


Figure 2. Stereoview of the molecular packing of 3,3′-bis(2-hydroxyethyl)-2,2′-bithiophene, **1**. Still lines represent intermolecular hydrogen bonds.

Scheme 2[a]



[a] THP = 2-tetrahydropyranyl. (i) NBS, DMF, (ii) Me_3SnLi, Me_3SnCl, THF, (iii) **3**, $Pd(PPh_3)_4$, toluene, (iv) HCl 10%, (v) LDA, Bu_3SnCl.

phene.[6] Attempts to prepare this compound by use of Grignard coupling were unsuccesful.[6]

The use of the tetrahydropyranyl group (THP) to protect the hydroxyl functionalities of **1** was justified by its low cost and by the fact that its NMR signals do not interfere with those of the aromatic protons of the reaction products. Consequently, the reaction course can be monitored by ^1H NMR. The reason for choosing the 2-hydroxylethyl group as the β substituent is that the starting monomer for the synthesis of **2**, namely 3-(2-hydroxyethyl)thiophene, is a commercially available product.

Bromination of **2** with *N*-bromosuccinimide in *N*-dimethylformamide[19] afforded the 2-bromo derivative **3** in high yield (90%). Several attempts to prepare the 2,5′-bis-tributylstannane **4** by action of butyllithium on **2**, in THF in the presence of TMEDA, and subsequent quenching of the dilithio derivative with tributyltin chloride resulted in a mixture of the di- and the monostannane. Attempts to separate the di- from the monostannane by chromathography or distillation led to partial destannylation. This behavior is very different from that of unsubstituted bithiophene whose 2,5-bis(tributyltin)-stannane is stable and can be chromatographed on silica gel. Complete conversion of **2** to **4** (>95% by ^{1}H NMR) could finally be obtained by action of freshly prepared lithium diisopropylamide on **2** in THF followed by quenching with Bu_3SnCl at −40 °C.

Attempts to obtain the monostannane **3a** by action of BuLi on the monobromo derivative **3** by halogen−metal exchange were also unsuccessful. **3a** could be prepared by reacting the 2-bromo derivative with Me_3SnLi and subsequent quenching with Me_3SnCl. A 60:40 mixture (according to ^{1}H NMR) of the desired monostannane **3a** and of the starting material **2** was obtained, which was used without further purification. Since the mixture did not contain the starting bromo derivative, the formation of **2** was due to partial hydrolysis of the highly unstable monostannyl derivative once formed. The conversion of **3** into **3a** was poor, and we were unable to obtain more favorable proportions of the monostannane.

The protected quater- and the sexithiophene, **3b** and **4a**, were obtained by reacting the monobromo derivative **3** with the mono and distannanes **3a** and **4**, respectively, in the presence of catalytic amounts of $Pd(PPh_3)_4$.

When the monobromo derivative **3** was reacted with the distannane **4** to afford the sexithiophene **4a**, there was also formation of quaterthiophene **3b**, probably because of partial destannylation of **4**. The amount of sexithiophene formed, estimated by ^{1}H NMR, was more than 70%. However, separation of **4a** from **3b** and from unidentified reaction products is difficult and the yield in pure (>98% by ^{1}H NMR) sexithiophene **4c** decreased dramatically (40%). Thus, developing better purification techniques is a key point for an efficient preparation of these oligomers.

Complete deprotection of sexithiophene **4b** and of quaterthiophene **3c** was easily achieved by reacting the substrates with 10% HCl for about 2 h.

One of the difficulties to deal with during the synthesis of substituted oligothiophenes is to achieve a good characterization of the substrates, since even a good microanalysis is not always sufficient to establish the length of the oligomers which have been obtained. In this respect, ^{13}C NMR has once again proved to be an invaluable technique to unambiguously establish the length of substituted oligothiophenes with the same regiochemistry, simply by counting the different types of quaternary carbons. Figure 3 shows the ^{13}C NMR spectrum of the aromatic region of **1**, **3c**, and **4b**. It can be seen that the resonances of the quaternary carbons which bear the substituents are easily distinguished from those of the junctions between adjacent rings, the former being characterized by shorter relaxation times and greater signal intensities (owing to the proximity with the hydrogen rich substituents).[20] The proton spectra of the aromatic region of **1**, **3c**, and **4b** are less informative since they only differ in the intensities of the singlet belonging to the protons of the inner rings.

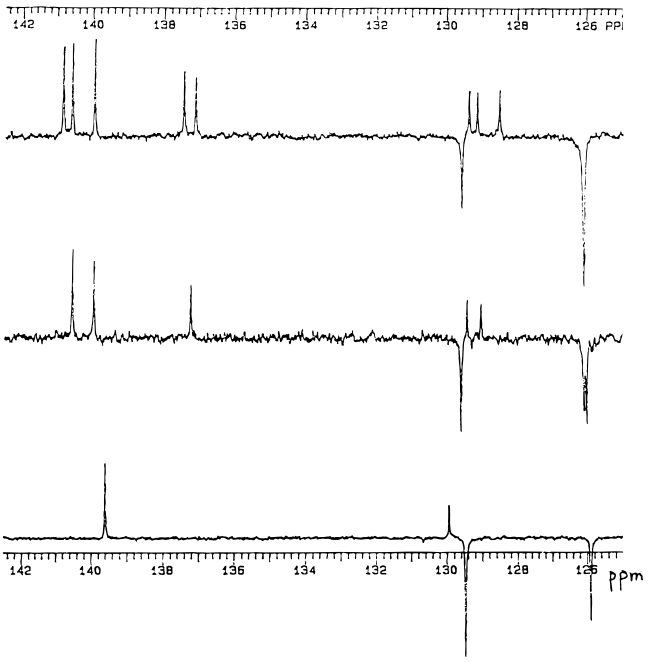


Figure 3. APT ^{13}C NMR spectrum of the aromatic region of bithiophene **1**, quaterthiophene **3c**, and sexithiophene **4b** (from bottom to top). APT = attached proton test; reverse phase signals are those pertaining to protonated carbons.

Thus far we have been unable to obtain crystals suitable for X-ray structure determinations from compounds **3b**, **3c** and **4a**, **4b**. In particular, **3c** and **4b** give crystals which are too small for X-ray structure determinations. It is well known that crystallization of oligothiophenes is difficult and only a few X-ray structures have been reported so far.[9−18,21] We are currently pursuing efforts in this direction.

3. MM3 Calculations. We have carried out force field calculations on bithiophene **1** and quaterthiophene **3c** to ascertain whether there is any influence of intramolecular H-bonding interactions on their conformational properties and, by extension, on those of sexithiophene **4b**. Since quaterthiophene **3c** contains not only two head-to-head but also one tail-to-tail bithiophene subsystems, we carried out force field calculations also on the tail-to-tail regioisomer of **1**, namely 4,4′-bis(2-hydroxyethyl)-2,2′-bithiophene. Moreover, we wanted also to find out whether elongation of the alkyl chain terminating with the hydroxyl group, needed to obtain a better solubility of the longer substrates (sexithiophene **4b** is insoluble in $CHCl_3$), has any influence on the conformational properties of head-to-head and tail-to-tail bithiophene. To this purpose we calculated the conformational energies of 3,3′- and 4,4′-bis(4-hydroxybutyl)-2,2′-bithiophene.

We have already reported MM2 force field calculations of the conformational energies of several oligothiophenes and have demonstrated that they furnish useful guidelines for the interpretation of the experimental results.[12,20,23] However, these kinds of calculations do not give a sufficiently good description of H-bonds, which are better evaluated using the MM3 force field.[25] Unfortunately, we have found that MM3 force field calculations

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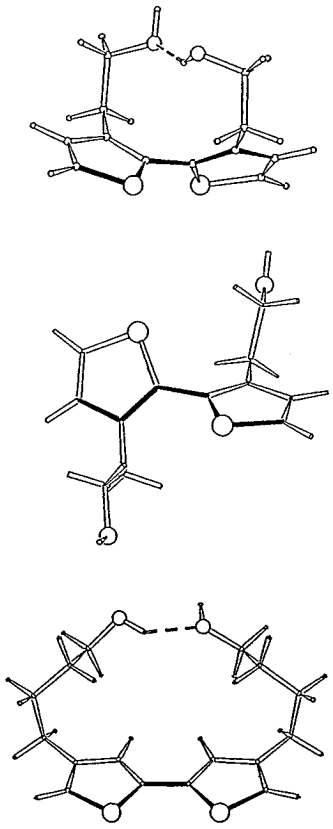

Figure 4. Top: MM3 calculated more stable *anti* conformation of 3,3′-bis(2-hydroxyethyl)-2,2′-bithiophene (**1**) (E = 26.6 kcal mol^{-1}, ω = 55°), stabilized by an intramolecular hydrogen bond over the *anti* conformation (E = 28.7 kcal mol^{-1}, ω = 50°) having the substituents pointing outside the ring plane as found in solid (middle). Bottom: MM3 calculated more stable *syn* conformation of 4,4′-bis(4-hydroxybutyl)-2,2′-bithiophene (E = 30.2 kcal mol^{-1}, ω = 0°), showing that elongation of the alkyl chain allows for the formation of an intramolecular H-bond also between tail-to-tail oriented substituents.

give energies and geometries for *syn* and *anti* 2,2′-bithiophene which are not in agreement with recently reported electron diffraction data.[24] As a consequence, we have modified some of the values of the parametrized constants of the standard MM3(92) package[25] (see Experimental Section).

Figure 4 (top) gives the more stable conformation of **1** (energy, E = 26.6 kcal mol^{-1}; inter-ring twist angle, ω = 55°), in which the two thiophene rings are in an *anti* orientation and the substituents point toward each other to form a hydrogen bond involving the oxygen atom of one chain and the hydrogen atom of the OH group of the adjacent chain. Interestingly, this conformation has a greater inter-ring twist angle than the *anti* conformation (E = 28.7 kcal mol^{-1}; ω = 50°) with the substituents pointing outside the plane of the thiophene ring to which they are bound in a way similar to that observed in solid (Figure 4, middle). MM3 calculations on the tail-to-tail regioisomer of **1**, 4,4′-bis(2-hydroxyethyl)-2,2′-bithiophene, show that the substituents are too far apart and too short to allow for the formation of an intramolecular H-bond. As a consequence, the *syn* (E = 27.02 kcal mol^{-1}, ω = 0°) and *anti* (E = 26.79 kcal mol^{-1}, ω = 30°) conformations have very close energies, as already observed for the corresponding tail-to-tail dimethyl and dihexyl bithiophenes.[22]

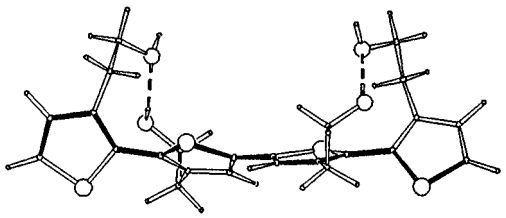

Figure 5. MM3 calculated more stable *anti-anti-anti* conformation of 3,3′,4″,3‴-tetrakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴-quaterthiophene **3c** (E = 55.0 kcal mol^{-1}; ω_1 = 55°, ω_2 = 30°, ω_3 = 55°) displaying a hydrogen bond in each one of the external head-to-head units. The *anti-syn-anti* conformation with a hydrogen bond in each one of the external head-to-head units but with the inner tail-to-tail unit in the *syn* orientation has almost the same energy (E_{syn} = 55.1 kcal mol^{-1}; ω_1 = 55°, ω_2 = 0°, ω_3 = 55°).

According to the calculations, in quaterthiophene **3c** there is a marked stabilization (4.6 kcal mol^{-1}) due to the formation of intramolecular hydrogen bonds in each one of the two terminal head-to-head bithiophene moieties. While the head-to-head moieties are "frozen" by the H-bonding in the *anti* conformation, the inner tail-to-tail unit can assume either a *syn* or an *anti* conformation without appreciable variation in the total energy of the molecule (E_{anti} = 55.0 kcal mol^{-1}; ω_1 = 55°, ω_2 = 30°, ω_3 = 55°. E_{syn} = 55.1 kcal mol^{-1}; ω_1 = 55°, ω_2 = 0°, ω_3 = 55°). The most stable conformation of **3c**, with the inner unit in the *anti* orientation, is reported in Figure 5.

MM3 calculations on 3,3′-bis(4-hydroxybutyl)-2,2′-bithiophene show that elongation of the alkyl chain has no effect on the conformational properties of a head-to-head unit. Indeed, the more stable conformation of this compound is the same as that found for the shorter substituents and reported in Figure 4 (left). However, calculations on the 4,4′-bis(4-hydroxybutyl)-2,2′-bithiophene regioisomer show that elongation of the alkyl chain allows for the formation of an intramolecular hydrogen bond also between tail-to-tail oriented substituents. In this case the H-bond-stabilized *syn* planar conformation (E = 30.2 kcal mol^{-1}; ω = 0°, reported in Figure 4, bottom) was found to be slightly more stable than the corresponding, H-bond stabilized, *anti* conformation (E = 30.6 kcal mol^{-1}; ω = 30°).

Discussion

Our results show that the synthesis *via* Stille's reaction[8] pathway is a good route to obtain head-to-head/tail-to-tail polyhydroxyloligothiophenes. Although organotin reagents are extensively employed in organic synthesis, they have been scarcely used for the preparation of substituted oligothiophenes. The synthesis of thiophene oligomers starting from 3-substituted monomers or larger building blocks is generally carried out using the cross-coupling reaction of thienylmagnesium bromides with thienyl bromides in the presence of nickel−phosphine catalysts.[26] In the course of the synthesis of compound **1** we were unable to prepare the Grignard derivative of 2-bromo-3-[2-(tetrahydropyranyloxy)ethyl]thiophene while we did not have problems in obtaining the corresponding stannane.[6] In our experience, Stille's reaction has provided a general route for the synthesis of odd- or even-

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numbered oligothiophenes with different types of regiochemistry of substitution and has given acceptably good yields even in cases of sterically crowded substituents.[22]

The X-ray structure of bithiophene **1** shows that intermolecular hydrogen-bonding has a profound effect on the conformation in solid and on the packing characteristics. All previous structural studies on bithiophenes, including those with long and sterically demanding alkoxy chains,[18] have always reported exactly coplanar *anti* conformations, due to a center of symmetry at the midpoint of the inter-ring bond.[9−12a] On the contrary, **1** has a strongly twisted conformation, with an unusually large twist angle between adjacent rings (67.5°). Such a large twist angle has not even been found between head-to-head substituted bithiophene subsystems of quaterthiophenes, for which the largest twist angle that has been measured was 46.4°.[12c] The strong hydrogen bonding ability of the OH functionality of the 2-hydroxyethyl substituents appears to be responsible for these unusual features of **1**. The intermolecular H-bonding—with each O−H group interacting with two other O−H groups belonging to different molecules and forming a six-centered ring—locks the bithiophene skeleton in an almost perpendicular conformation. This leads to loss of π conjugation and to elongation of the inter-ring carbon−carbon bond, in agreement with the results of theoretical calculations.[27] Owing to the H-bonding interactions, the packing characteristics of **1** (see Figure 2) are also completely different from those of all other oligothiophenes whose X-ray structure has been reported so far and which are characterized by the "herringbone" crystal packing common to most planar or like-planar organic molecules.[9−15,28]

The λ_{max} values of **1** (242 nm in $CHCl_3$ and 242 nm in CH_3OH), **3c** (336 nm in $CHCl_3$ and 334 nm in CH_3OH), and **4b** (352 nm in CH_3OH; this compound is insoluble in chloroform) are the smallest maximum UV absorptions ever measured in solution for α-conjugated bi-, quater-, and sexithiophenes, respectively. The maximum UV absorption of oligo and polythiophenes depends on the π conjugation, which is related to the degree of planarity of these compounds and which depends on the nature of the substituents and on the regiochemistry of substitution.[1a,3] The low λ_{max} values of **1**, **3c**, and **4b** indicate low π conjugation and largely twisted conformations for these compounds in solution. For the dimer and the tetramer a change of the solvent from $CHCl_3$ to CH_3OH causes a very small blue shift of the maximum UV absorption, 4 and 2 nm, respectively, indicating that the formation of intermolecular H-bonds with the solvent only slightly affects the λ_{max} values of the substrates. The results of MM3 calculations suggest that in chloroform **1** and **3c** already exist in very twisted conformations, stabilized by intramolecular H-bonds, such as the one depicted in Figure 4 (left). However, it is difficult to establish how much of the loss of π conjugation and of the consequent decrease of the λ_{max} values of **1**, **3c**, and **4b** is due to intramolecular and how much to intermolecular H-bonding, since both factors act in the direction of increasing the inter-ring twist angles and decreasing the π conjugation. Nevertheless, the data suggest that for 2-hydroxylethyl groups as β substituents inter- as well as intramolecular H-bond interactions amplify the twisting between adjacent rings and induce a hypsochromic shift of the λ_{max} values.

As shown by MM3 calculations, the presence of alternating head-to-head and tail-to-tail bithiophene subsystems should confer to quaterthiophene **3c** (and, by extension, to sexithiophene **4b** and to longer oligothiophenes with the same regiochemistry) a great conformational mobility. Indeed, while the head-to-head fragments are "frozen" in the *anti*, largely twisted, conformation by the formation of an intramolecular H-bond between the substituents, the tail-to-tail fragments are "free" to assume either a *syn* planar or an *anti* quasiplanar conformation. The calculations also show that the elongation of the alkyl chains terminating with OH groups leads to the possibility of formation of intramolecular H-bonds not only in the head-to-head but also in the tail-to-tail moieties. Thus, with longer substituents, the tail-to-tail moieties could compete with the head-to-head ones for the formation of intramolecular hydrogen bonds. In consequence, intramolecular H-bonding is no longer confined to the head-to-head fragments but can be extended over other points of the molecular skeleton, eventually limiting the conformational mobility of the system. This also implies that the degree of twisting between adjacent rings induced by the formation of H-bonds could be tuned by an appropriate choice of the length of the chains terminating with the OH functionality.

Finally, it should be remarked that the polyhydroxyl oligothiophenes described here are potential multidentate hosts for a variety of substrates and that all their properties, including the conformation and the maximum UV absorption, should be sensitive to molecular recognition events. Work is currently in progress in this direction.

Conclusion

In conclusion, we have shown that intermolecular hydrogen bonding interactions between the hydroxyl groups cause 3,3′-(2-hydroxyethyl)-2,2′-bithiophene (**1**) to display a solid state conformation and a packing arrangement which are different from those of all other oligothiophenes whose structures have been reported thus far. To our knowledge, this is the first experimental evidence that functionalization with alkyl chains containing terminal OH groups is a way to tailor the solid state organization of oligothiophenes through H-bonding.

Furthermore we have efficiently synthesized the dimer and the trimer of **1** (a quater and a sexithiophene, respectively) *via* the Stille's reaction, *i.e.* through palladium(0)-catalyzed cross-coupling of the appropriate stannanes and bromides of the hydroxypyranyl derivative of **1**. These compounds are well characterized by ^{13}C NMR, which is the most valuable technique to establish not only the purity degree but also the length of the

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oligomers having the same regiochemistry. The λ_{max} values of the dimer and the trimer of **1** indicate largely twisted conformations in solution. Force field MM3 calculations suggest this to be also the result of intramolecular H-bonding between 2-hydroxyethyl substituents which favors highly twisted arrangements of the head-to-head moieties of the substrates.

Future work will include the synthesis of derivatives with longer alkyl chains terminating with hydroxyl groups with the goal of modulating the conformational properties in solid and in solution through the interplay of inter- and intramolecular H-bonding interactions.

Experimental Section

Synthesis of Materials. General Procedures. Tributyltin chloride, trimethyltin chloride, *n*-butyllithium, *N*-bromosuccinimide, 3-(2-hydroxyethyl)thiophene, and tetrakis-(triphenylphosphine)palladium were purchased from Janssen. All reactions were carried out under an argon atmosphere. Flash chromatographies were carried out on silica gel (230−400 mesh ASTM). UV spectra were obtained with a Perkin-Elmer 554 spectrometer (chloroform). ^{1}H and ^{13}C NMR spectra were obtained using a Varian VXR 200 spectrometer (200 and 50 MHz, respectively) using $CDCl_3$ or CD_2Cl_2 as the solvents and TMS as the internal standard.

2-Bromo-3,3′-bis[2-(tetrahydropyranyloxy)ethyl]-2,2′-bithiophene (3). To a solution of 1.0 g (2.37 mmol) of 3,3′-bis[2-(tetrahydropyranyloxy)ethyl]-2,2′-bithiophene[6] (**2**) in 50 mL of anhydrous DMF at $T = -20$ °C were added 0.42 g (2.37 mmol) of *N*-bromosuccinimide stepwise. The mixure was allowed to warm to room *T* and stirred overnight. The mixture was then quenched with ice and the aqueous phase treated with methylene chloride. The organic layer was washed with brine, dried over Na_2SO_4, and evaporated. The resulting residue was purified by flash chromatography (CH_2Cl_2:ethyl acetate 85:15 v/v). A 1.07 g amount of a pale yellow oil were obtained (90% yield). ^{1}H NMR ($CDCl_3$/TMS): 7.30 (d, $J = 5.5$ Hz, 1H), 7.04 (d, $J = 5.5$ Hz, 1H), 7.03 (s, 1H), 4.55 (m, 2H), 3.9 (m, 4H), 3.5 (m, 4H), 2.8 (m, 4H), 1.6 (m, 12H). ^{13}C NMR ($CDCl_3$/TMS): 139.9, 139.5, 131.9, 131.1, 129.0, 128.2, 126.1, 112.0, 98.6, 67.2, 67.0, 62.1, 30.6, 29.2, 25.4, 19.4 ppm. Anal. Calcd for $C_{22}H_{29}O_4S_2$: C, 52.69; H, 5.83. Found: C, 52.81; H, 5.85.

5-(Trimethylstannyl)-3,3′-[2-(tetrahydropyranyloxy)-ethyl]-2,2′-bithiophene (3a). To a flask immersed in a bath at −10 °C and containing 0.88 g (0.12 moles) of lithium wire and 10 mL of dry THF were added dropwise 2.5 g (0.012 mmol) of trimethyltin chloride dissolved in 40 mL of THF. The mixture was stirred overnight at room temperature. A 24 mL (6.0 mmol) volume of this trimethyltin lithium solution were added to a solution of 1 g (2.0 mmol) of **3** in 20 mL of THF, and the mixture was stirred for 2 h at room temperature. The solution was then cooled at 0 °C, and 0.4 g (2.0 mmol) of trimethyltin chloride dissolved in 20 mL of THF were added dropwise. The solution was stirred at ambient temperature for 1 h and then was quenched with a saturated solution of NH_4Cl and treated with ethyl ether, and the organic phase was separated, washed with brine, dried over $MgSO_4$, and evaporated. The excess of trimethyltin chloride was evaporated under vacuum. A 0.97 g amount of a yellow green liquid were obtained, which, according to ^{1}H NMR contained 60% of **3a** and 40% of the starting material **2**. The mixture was used without further purification. ^{1}H NMR ($CDCl_3$/TMS): 7.26 (d, $J = 5.5$ Hz, 1H), 7.02 (d, $J = 5.5$ Hz, 1H), 7.09 (s, 1H), 4.6 (m, 2H), 3.9 (m, 4H), 3.5 (m, 4H), 2.85 (m, 4H), 1.6 (m, 12H), 0.4 (s, 9 H) ppm. ^{13}C NMR ($CDCl_3$/TMS): 138.4, 138.2, 138.0, 137.3, 129.0, 125.3, 98.5, 67.4, 62.0, 30.6, 29.1, 25.5, 19.4, −8.3 ppm.

3,3′,4″,3‴-Tetrakis[2-(tetrahydropyranyloxy)ethyl]-2,2′:5′,2″:5″,2‴-quaterthiophene (3b). To a solution containing 0.154 mmol of **3a** in 30 mL of toluene was added dropwise a solution of 85 mg (0.169 mmol) of **3** in 20 mL of toluene and 9 mg (0.008 mmol) of $Pd(PPh_3)_4$. The mixture was refluxed overnight. The solution was then treated with 2 N HCl, neutralized with a 10% solution of $NaHCO_3$, washed twice with brine, dried over $MgSO_4$, and evaporated. The residue was chromatographed on silica gel using CH_2Cl_2: ethyl acetate 85:15 v/v as the eluent. A 87 mg (67% yield) amount of **3b** as a viscous yellow liquid were obtained. ^{1}H NMR ($CDCl_3$/TMS): 7.38 (d, $J = 5.0$ Hz, 2H); 7.20 (s, 2H); 7.12 (d, $J = 5.0$ Hz, 2H); 4.60 (m, 4H); 3.7 (m, 16 H); 2.9 (m, 8H); 1.6 (m, 12H) ppm. ^{13}C ($CDCl_3$/TMS): 140.5, 139.9, 137.2, 129.6, 129.4, 129.0, 126.1, 125.9 ppm. $\lambda_{max}(CHCl_3) = 340$ nm. Anal. Calcd for $C_{44}H_{58}O_8S_4$: C, 62.68; H, 6.93. Found: C, 62.79; H, 6.95.

3,3′,4″,3‴-Tetrakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴-quaterthiophene (3c). A 80 mg (0.095 mmol) amount of **3b** were dissolved in 10 mL of THF and 5 mL of 10% HCl (v/v). The mixture was refluxed for 2 h, and then the THF was evaporated and 20 mL of ethyl acetate was added. The mixture was neutralized with a saturated solution of $NaHCO_3$, washed twice with brine, dried over Na_2SO_4, and evaporated. The residue was chromatographed on silica gel using CH_2Cl_2:acetone 50:50 v/v as the eluent. A 38 mg (79% yield) amount of a pale yellow solid, mp 55°C, was obtained. ^{1}H NMR ($CDCl_3$/TMS): 7.15 (d, $J = 5.5$ Hz, 2H); 7.29 (s, 2H); 7.51 (d, $J = 5.5$ Hz, 2H); 3.8 (m, 8H); 2.8 (m, 12 H) ppm. ^{13}C ($CDCl_3$/TMS): 141.5, 140.6, 137.4, 130.2, 129.5, 129.4, 126.9, 126.7, 62.8, 62.6, 33.3, 33.2 ppm. $\lambda_{max}(CHCl_3) = 336$ nm. Anal. Calcd for $C_{24}H_{26}O_4S_4$: C, 56.89; H, 5.17. Found: C, 56.73; H, 5.16.

2,5-Bis(tributylstannyl)-3,3′-[2-(tetrahydropyranyl-oxy)ethyl]-2,2′-bithiophene (4). To a solution of 0.27 mL (1.92 mmol) of diisopropylamide in 10 mL of dried THF mantained at −10 °C was added dropwise 0.705 mL (1.77 mmol) of 2.5 M *n*-butyllithium. The temperature was then lowered to −40 °C, and to the mixture was added a solution of 300 mg (0.71 mmol) of 3,3′-bis[2-(tetrahydropyranyloxy)-ethyl]-2,2′-bithiophene[6] and 0.48 mL (1.77 mmol) of tributyltin chloride in 10 mL of dried THF. The solution was slowly raised to room temperature and stirred overnight. The reaction was monitored by thin layer chromatography using cyclohexane:ethyl acetate 90:10 as the eluent. Finally, the reaction mixture was quenched with a saturated solution of NH_4Cl and treated with ethyl ether and the organic phase was washed with brine and separated, dried over $MgSO_4$, and evaporated. A 0.64 g amount of **2a** of a yellow-green oil (>95% pure by ^{1}H NMR) was obtained. ^{1}H NMR ($CDCl_3$/TMS): 7.06 (s, $J_{H,Sn} = 24.0$ Hz, 2H), 4.6 (m, 2H), 3.8 (m, 4H), 3.5 (m, 4H), 2.8 (m, 4H), 0.7−1.9 (m, 66 H) ppm. ^{13}C NMR ($CDCl_3$/TMS): 139.0, 137.4, 136.6, 136.0, 99.6, 67.6, 61.9, 30.6, 28.9, 27.2, 26.8, 25.5, 19.4, 13.5, 10.7 ppm.

3,3′,4″,3‴,4⁗,3⁗′-Hexakis[2-(tetrahydropyranyloxy)-ethyl]-2,2′:5′,2″:5″,2‴:5‴,2⁗:5⁗,2⁗′-sexithiophene (4a). To a solution of 710 mg (0.71 mmol) of **2a** and 45 mg (0.039 mmol) of PdPPh3 in 10 mL of toluene distilled over metallic sodium were added 710 mg (1.42 mmol) of **3** dissolved in 10 mL of toluene. The solution was refluxed overnight and then quenched with 2 N HCl and neutralized with a 10% solution of $NaHCO_3$. The organic layer was washed with brine and separated, dried over $MgSO_4$, and evaporated. The residue was purified by flash chromatography using cyclohexane added with increasing amounts (20 to 40% v/v) of ethyl acetate. A 360 mg amount of **3b** as a yellow-orange viscous liquid was obtained (40% yield). ^{1}H NMR ($CDCl_3$/TMS): 7.35 (d, $J = 5.0$ Hz, 2H), 7.19 (s, 4H), 7.09 (d, $J = 5.0$ Hz, 2H), 4.6 (m, 6H), 3.4−3.9 (m, 24 H), 2.8 (m, 12 H), 1.6 (m, 36 H) ppm. ^{13}C NMR ($CDCl_3$/TMS): 140.8, 140.5, 139.9, 137.4, 137.1, 129.6, 129.4, 129.2, 128.5, 126.2, 98.9, 67.5, 67.3, 62.3, 62.2, 31.0, 29.9, 29.8, 25.9, 19.8. $\lambda_{max}(CHCl_3) = 356$ nm. Anal. Calcd for $C_{66}H_{86}O_{12}S_6$: C, 6.86; H, 5.17. Found: C, 62.85; H, 6.87.

3,3′,4″,3‴,4⁗,3⁗′-Hexakis(2-hydroxyethyl)-2,2′:5′,2″:5″,2‴:5‴,2⁗:5⁗,2⁗′-sexithiophene (4b). A 1 g (0.79 mmol) amount of **4a** was dissolved in 50 mL of THF and 20 mL of 10% HCl (v/v). The mixture was refluxed for 2 h, and then the THF was evaporated and 100 mL of ethyl acetate was added. The mixture was neutralized with a saturated solution of $NaHCO_3$, washed twice with brine, dried over Na_2SO_4, and

evaporated. The residue was chromatographed on silica gel using CH_2Cl_2:THF:MeOH 60:35:5 v/v as the eluent. A 440 mg (73% yield) amount of a pale yellow solid, mp 123 °C, was obtained. ^{1}H NMR ($CDCl_3$/TMS): 7.50 (J = 5.0 Hz, 2H), 7.31 (s, 4H), 7.13 (J = 5.0 Hz, 2H), 3.8 (m, 12H), 2.7 (m, 12H) ppm. ^{13}C NMR ($CDCl_3$/TMS): 141.4, 141.1, 140.3, 138.4, 138.0, 130.2, 130.1, 130.0, 129.4, 127.3, 126.8, 62.5, 62.4, 33.8 ppm. $\lambda_{max}(CH_3OH)$ = 352 nm. Anal. Calcd for $C_{36}H_{38}O_6S_6$: C, 56.96; H, 5.05. Found: C, 56.74; H, 5.03.

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Supporting Information Available: ^{1}H NMR spectrum of 2-(trimethylstannyl)-3,3′-[2-(tetrahydropyranyloxy)ethyl]-2,2′-bithiophene and ^{13}C NMR spectrum of 2,5-bis(tributylstannyl)-3,3′-[2-(tetrahydropyranyloxy)ethyl]-2,2′-bithiophene in $CDCl_3$ (2 pages). This material is contained in 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.

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