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Electrochemical Synthesis Based on the Oxidation of 1-(4-(4-Hydroxyphenyl)piperazin-1-yl)ethanone in the Presence of Nucleophiles

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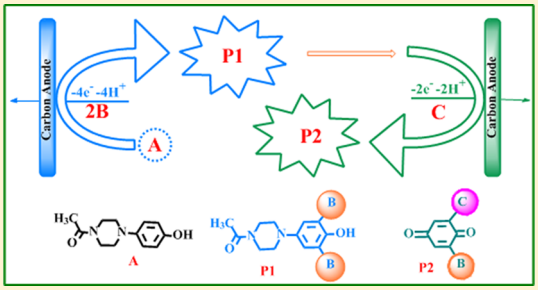
Supporting Information

ABSTRACT: Electrochemical syntheses of new arylthiobenzazoles were carried out by electrochemical oxidation of 1-(4-(4-hydroxyphenyl)-piperazin-1-yl)ethanone in the presence of 2-mercaptobenzothiazole and 2-mercaptobenzoxazole. Our voltammetric data indicate that electrochemically generated *p*-quinone imine participates in a Michael addition reaction with 2-*SH*-benzazoles leading to the disubstituted 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethanone. Also, a plausible mechanism for the oxidation of 1-(4-(3,5-bis(benzo[*d*]thiazol-2-ylthio)-4-hydroxyphenyl) in the presence of *p*-toluenesulfinic acid is presented. 1-(4-(3,5-Bis(benzo[*d*]thiazol-2-ylthio)-4-hydroxyphenyl) was converted into 2-(benzo[d]thiazol-2-ylthio)-6-tosylcyclohexa-2,5-diene-1,4-dione through a Michael-type addition of *p*-toluenesulfinic acid to anodically generated *p*-quinone imine, replacing 2-mercaptobenzothiazole and followed by hydrolysis.



Mercaptobenzazoles are known for their various biological activities such as antibacterial,[1] antiviral,[2] antiproliferative,[3] and antifungal.[4] Also, some therapeutic agents containing the 2-arylthiobenzothiazole moiety include inhibitors of cathepsin-D and a potent heat shock protein-90 inhibitors. These compounds also act as antimicrobial agents especially against *Piricularia oryzae* and *Xanthomonas oryzae*.[5]

On the other hand, phenylpiperazines are important pharmaceutics that can be found in biologically active compounds across a number of different therapeutic areas,[6] such as HIV protease inhibitor,[7] antipsychotic agents,[8] antifungal,[9] and antitumor agents.[10] For example ketoconazole has been used for oral treatment of systemic fungal infections.[11] Also, quinones are of considerable interest because many drugs such as doxorubicin in cancer chemotherapy contain quinones.[12] Some of them also exhibit antitumor and antimalarial activities,[13] and many of them are also involved in enzyme inhibition and DNA cross-linking.[14]

According to these data, we think that synthesis of organic compounds with both structures of 2-mercaptobenzothiazole (**2a**) or 2-mercaptobenzoxazole (**2b**) and phenylpiperazine or quinone would be useful from the point of view of pharmaceutical properties. This idea prompted us to investigate electrochemical oxidation of 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethanone (**1**) in the presence of 2-*SH*-benzazoles (**2a**,**b**) as nucleophiles and present a one-pot electrochemical method for the synthesis of arylthiobenzazoles derivatives (compounds **7a**,**b**) (Scheme 1). This reaction is carried out in a single step with high atom economy in ambient conditions and in an undivided cell using a carbon electrode. In this work, also, electrochemical oxidation of 1-(4-(3,5-bis(benzo[*d*]thiazol-2-ylthio)-4-hydroxyphenyl) (**7a**) in the presence of *p*-toluenesulfinic acid (**9**) and synthesis of 2-(benzo[*d*]thiazol-2-ylthio)-6-tosylcyclohexa-2,5-diene-1,4-dione (**13**) have been investigated (Scheme 2).

A cyclic voltammogram of 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethanone (**1**) in water (containing phosphate buffer, c = 0.2 M, pH = 2.0)/acetonitrile mixture (80/20 v/v) is shown in Figure 1, curve a. Under these conditions, the voltammogram shows one anodic (A_1) and two cathodic peaks (C_1 and C_s). Anodic and cathodic peaks A_1 and C_1 are counterparts and correspond to the transformation of **1** to *p*-quinone imine **1ox** (Scheme 1) and vice versa within a quasi-reversible two-electron process.[15] The peak current ratio (I_p^{C1}/I_p^{A1}) is dependent on pH and scan rate. It increases with decreasing pH and increasing scan rate. The cathodic peak C_1 disappears in basic solutions and/or in low potential sweep rates.[15] The cathodic peak C_s (s = side reactions) has a different behavior. The current of this peak increases with increasing pH and its normalized current ($I_{pCs}/v^{1/2}$) increases with decreasing scan rate. This peak is related to the occurrence of side reactions such as hydrolysis, hydroxylation and/or dimerization reaction, under the experimental conditions.[15,16]

The oxidation of **1** in the presence of 2-mercaptobenzothiazole (**2a**) as a nucleophile was studied in some detail. Figure 1, curve b, shows the cyclic voltammogram obtained for **1** in the presence of **2a**. Comparison of this voltammogram with the cyclic voltammogram of **1** in the absence of **2a** shows that (a) the cathodic peak C_1 decreased intensively, (b) the anodic peak

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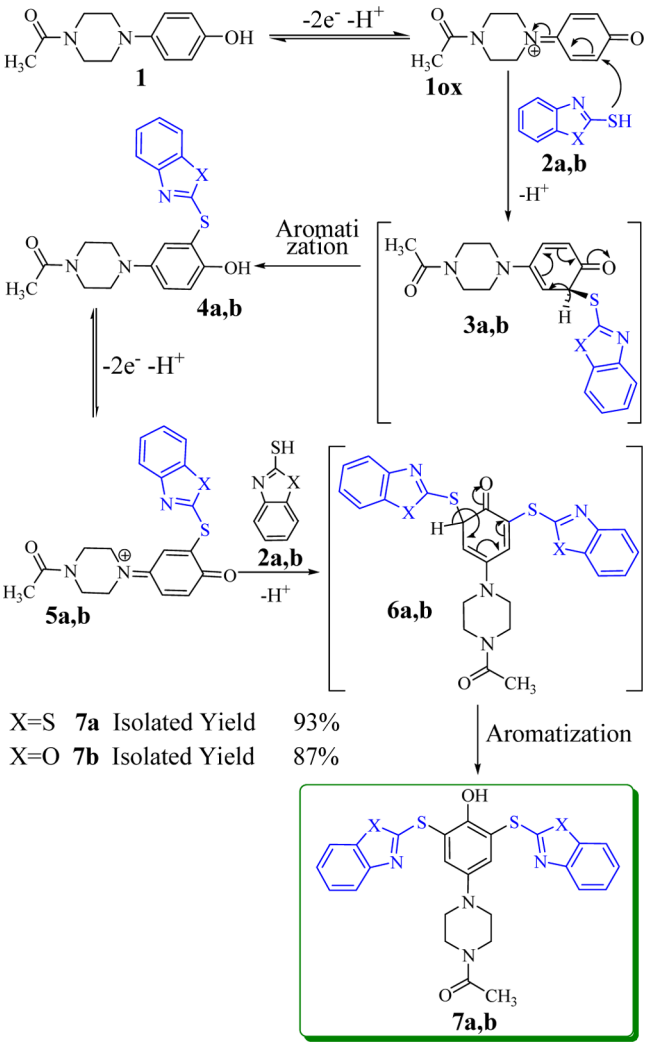
Scheme 1. Proposed Mechanism for the Electrochemical Oxidation of 1-(4-(4-Hydroxyphenyl)piperazin-1-yl)ethanone in the Presence of the 2-*SH*-benzazoles



A_1 increased slightly, and (c) a new anodic peak (A_2) appeared at more positive potentials. The occurrence of a chemical reaction after electron transfer process is supported by the decreasing of peak C_1 during the reverse scan, which could indicate that **1ox** formed at the surface of the electrode is consumed by a chemical reaction with **2a**. In Figure 1, curve d is the cyclic voltammogram of the isolated final product (**7a**). Comparison of this curve with curve b shows that peak A_2 is related to the electrooxidation of **7a**.

Curve c in Figure 1 shows the irreversible oxidation of **2a**.[17] Wittstock and co-workers reported that the main product in oxidation of 2-mercaptobenzoxazole is bis(benzoxazolyl) disulfide.[18]

Controlled-potential coulometry was performed in a cell containing 0.25 mmol of **1** and 0.50 mmol of **2a**. Cyclic voltammetric analysis was carried out during the coulometry. It is shown that, proportional to the advancement of coulometry, the anodic peak A_1 decreases. This peak disappears when the charge consumption becomes $4e^-$ per molecule of **1**. Coulometry, cyclic voltammetry and spectroscopic data of the final product obtained from exhaustive oxidation of **1** in the presence of **2a**, allow us to propose the following mechanism for the electrooxidation of **1** in the presence of **2a** and **2b** (Scheme 1).

The oxidation of **7a** is more difficult than the oxidation of **1** by virtue of the presence of electron-withdrawing 2-mercaptobenzothiazole groups on **7a**. Therefore, the oxidation of **7a** was prevented during the reaction because of the presence of the electron-withdrawing group as well as by the insolubility of it in the water/acetonitrile (45/15 v/v) solution. According to our results, the anodic peak A_2 pertains to the oxidation of **7a** to related *p*-quinone-imine **8a** (Scheme 2). Obviously, the cathodic peak C_2 corresponds to the reduction of **8a** to **7a**.

The oxidation of **7a** in the presence of *p*-toluenesulfinic acid (**9**) (Scheme 2) as a nucleophile was studied in next step. Figure 2, curve b, shows the cyclic voltammogram obtained for **7a** in the presence of **9**. Comparison of this voltammogram with cyclic voltammogram of **7a** in the absence of **9** (curve a), shows that; a) the cathodic peaks C_2 and C_s decreased and b) a new anodic peak (A_3) appeared at more positive potentials. The peak current ratio (I_p^{A2}/I_p^{A3}) is related to the scan rate and increases with increasing it. The occurrence of a chemical reaction after electron transfer process is supported by the decreasing of peak C_2 during the reverse scan, which could indicate that *p*-quinone-imine **8a** (Scheme 2) formed at the surface of the electrode is consumed by a chemical reaction with **9**.

Comparison of voltammograms b and c reveals that the peak A_3 corresponds to the oxidation of toluenesulfinic acid **9** linked covalently to **7a**.

Controlled-potential coulometry was performed in a cell containing 0.22 mmol of **7a** and 0.22 mmol of **9** at 0.60 versus Ag/AgCl. Cyclic voltammetric analysis was carried out during the coulometry shows when peak A_2 disappears, the charge consumption becomes more than $2e^-$ per molecule of **7a**.

The cyclic voltammetry results accompanied by the molecular mass of 430 (M + 3H) of final product allow us to propose an EC_1C_2 mechanism for the electrochemical oxidation of **7a** in the presence **9** (Scheme 2). "*E*" represents an electron transfer at the electrode surface, and "*C*" represents a homogeneous chemical reaction (C_1 = addition−elimination and C_2 = hydrolysis). In this mechanism, the key step in the formation of *p*-benzoquinone **12** is replacement of an strong nucleophile (*p*-toluenesulfinic acid) with a weak nucleophile (2-mercaptobenzothiazole) after generation Michael acceptor. The unexpected number of transferred electrons was explained by the oxidation of separated mercaptobenzothiazole (**2a**) from **7a** and formation of bis(mercaptobenzothiazolyl) disulfide.[18]

The possibility of the direct synthesis of **12** was also examined by the stirring of a solution containing **7a** and **9** (in water/acetonitrile (50/50) v/v, pH = 2.0) (without oxidation). However, our results did not show any evidence of synthesis of **12**.

In a recent published paper,[15] we have shown that the *p*-quinone-imine derived from oxidation of **1** participates in Michael type addition reaction with **9** as a nucleophile and via an *EC* mechanism converts to the 1-(4-(4-hydroxy-3-tosylphenyl)piperazin-1-yl)ethanone (**13**) (Scheme 3). In the second strategy for electrochemical synthesis of **12**, we examined the synthesis of **12** via electrochemical synthesis of **13** in the first step[15] and electrooxidation of **13** in the presence of **2a** in the second step (Scheme 3). Figure 3 curve a, shows the cyclic voltammograms obtained for **13** (synthesized according to ref 15). The voltammogram exhibits one anodic

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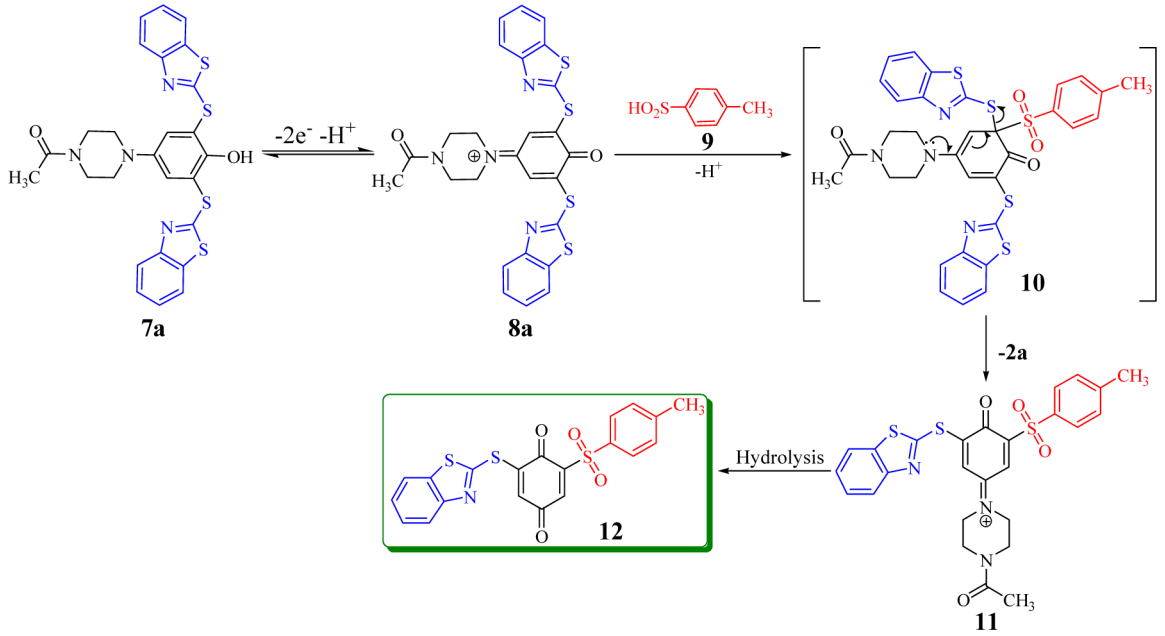
Scheme 2. Proposed Mechanism for the Electrochemical Oxidation of 1-(4-(3,5-Bis(benzo[d]thiazol-2-ylthio)-4-hydroxyphenyl)piperazin-1-yl)ethanone in the Presence of *p*-Toluenesulfinic Acid



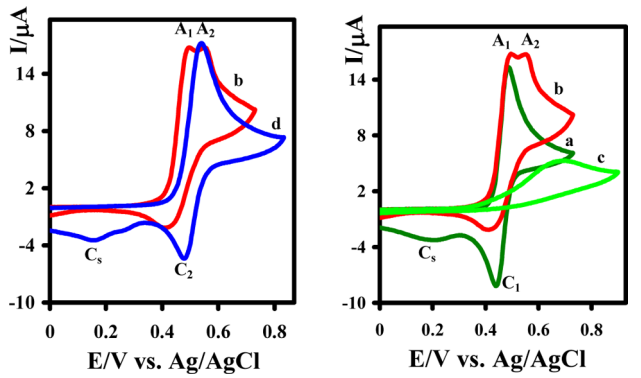


Figure 1. Cyclic voltammograms of (a) 1.0 mM 1-(4-(4-hydroxyphenyl) piperazin-1-yl)ethanone (**1**); (b) 1.0 mM **1** in the presence of 1.0 mM 2-mercaptobenzothiazole (**2a**); (c) 1.0 mM **2a** in the absence of **1**; (d) 1.0 mM of the final product (**7a**) at a glassy carbon electrode in water (phosphate buffer, c = 0.2 M, pH = 2.0)/acetonitrile (80/20) solution. Scan rate 100 mV s^{-1}. t = 25 ± 1 °C.

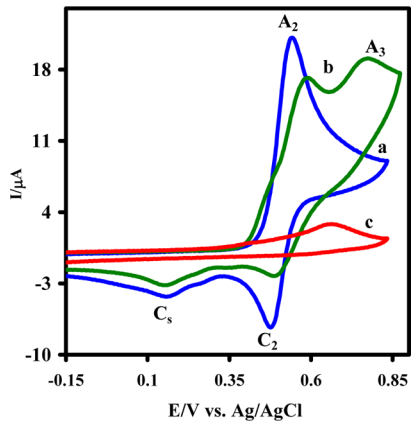


Figure 2. Cyclic voltammograms of (a) 1.0 mM **7a**; (b) 1.0 mM **7a** in the presence of 1.0 mM *p*-toluenesulfinic acid; (c) 1.0 mM *p*-toluenesulfinic acid. Scan rate 150 mV s^{-1}, at a glassy carbon electrode in water (phosphate buffer, c = 0.2 M, pH = 2.0).)/acetonitrile (50/50 v/v). t = 25 ± 1 °C.

peak (A_4) in the positive-direction scan and two cathodic peaks (C_4 and C_s) in the negative-direction scan. Anodic and cathodic peaks A_4 and C_4 are counterpart and are correspond to the transformation of **13** to its corresponding *p*-quinone-imine **13ox** (Scheme 3) and vice versa.[15,16]

The oxidation of **13** in the presence of **2a** as a nucleophile was studied in some detail. We expected that **13** via an *EC* mechanism convert to compound **14** (Scheme 3). Figure 3, curve b, shows the cyclic voltammogram obtained for **13** in the presence of **2a**. The voltammogram clearly exhibits an increase in anodic peak A_4. This is unexpected result for an *EC* mechanism. For an *EC* reaction, the flux of **13** is not changed very much, so that any index of that flux, such as the limiting current is only slightly perturbed. On the other hand, the limiting current for a catalytic reaction (*EC′*) (a reaction mechanism in which the sequence involves a catalytic reaction of the product after the electron transfer) will be increased because **13** is continuously replenished by the chemical reaction (Scheme 3).[19]

Controlled-potential coulometry was performed in a cell containing 0.2 mmol of **13** and 0.2 mmol of **2a**. The continual increase of n_{app} (charge consumed) up to $8e^-$ under these conditions confirms catalytic oxidation of **2a** by **13ox**. Since, this reaction (*EC′*) competes with substitution reaction (*EC*), in this strategy we could not synthesize successfully compound **12** in a good yield and purity.

In the third strategy for electrochemical synthesis of disubstituted-*p*-benzoquinone **12**, we examined a one-pot process for the synthesis of **12** via electrochemical oxidation of **1** in the presence of both **2a** and **9**. In this strategy, electrochemical synthesis of **12** was also unsuccessful. Because of the higher nucleophilicity of **9**, the generation of *p*-quinone-imine (**1ox**) is first followed by a Michael addition of **9** on **1ox**, producing the 1-(4-(4-hydroxy-3-tosylphenyl)piperazin-1-yl)-

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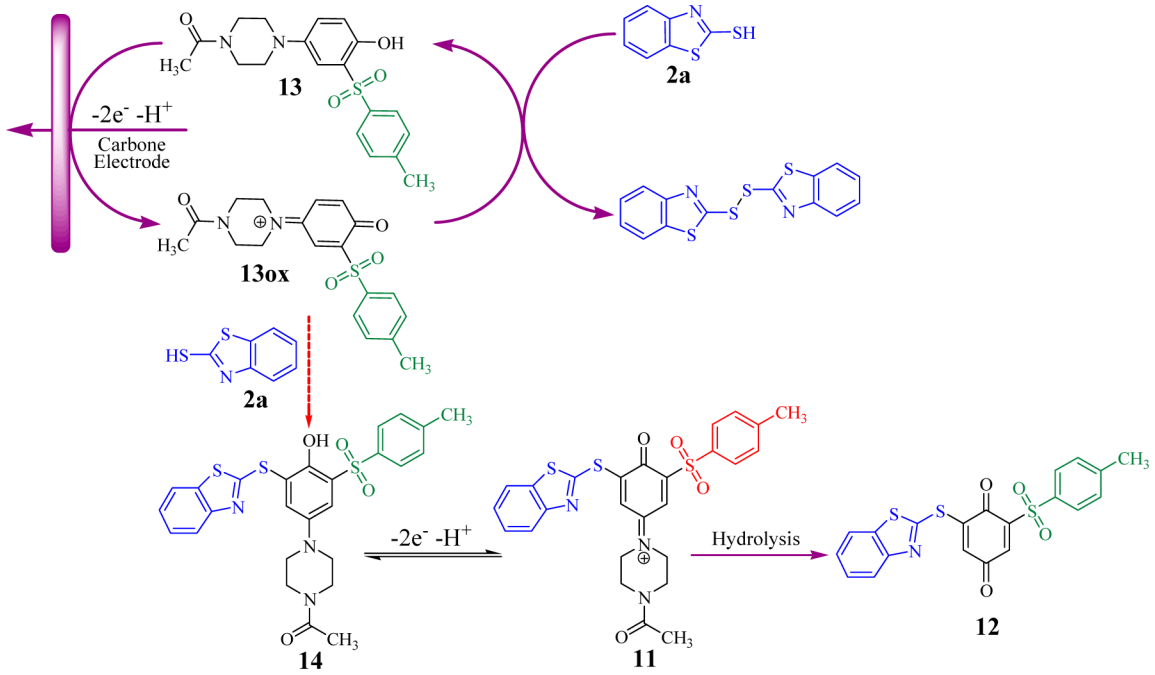
Scheme 3. Proposed Mechanism for the Electrochemical Oxidation of 1-(4-(4-Hydroxy-3-tosylphenyl)piperazin-1-yl)ethanone in the Presence of 2-Mercaptobenzothiazole



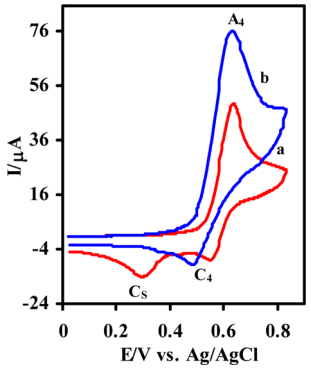


Figure 3. Cyclic voltammograms of (a) 1.0 mM 1-(4-(4-hydroxy-3-tosylphenyl)piperazin-1-yl)ethanone (**13**) and (b) 1.0 mM **13** in the presence of 1.0 mM 2-mercaptobenzothiazole. Scan rate 700 mV s^{-1}. Other conditions are the same as same as Figure 2.

ethanone (**13**) as the major product.[15] As described in second strategy, the competition of catalytic reaction with substitution reaction causes that in this strategy we could not produce successfully compound **12** in a good yield and purity.

Finally, the results of this work show that **1** is oxidized to their respective *p*-quinone-imine. The formed *p*-quinone-imine is attacked by 2-*SH*-benzazoles to form disubstituted 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethanone (**7a,b**) as the final products. The reaction mechanism for anodic oxidation of **1** in the presence of **2a,b** is presented in Scheme 1. This method provides a one-pot procedure in ambient conditions with high atom economy for the synthesis of compounds **7a,b**. Also, for the synthesis of **1** with two different substituent groups, electrochemical oxidation of **7a** has been performed in the presence of *p*-toluenesulfinic acid. Our results show that oxidized form of **7a** is attacked by *p*-toluenesulfinic acid to form 2-(benzo[*d*]thiazol-2-ylthio)-6-tosylcyclohexa-2,5-diene-1,4-dione (**12**) as a final product. In addition, in this work we examined two other strategies for the synthesis of **12**. In these strategies, because of the competition of catalytic reaction with substitution reaction, we could not produce successfully compound **12** in a good yield and purity.

EXPERIMENTAL SECTION

Apparatus and Reagents. Reaction equipment was described in a previous paper.[20] 1-(4-(4-Hydroxyphenyl)piperazin-1-yl)ethanone, 2-mercaptobenzothiazole, 2-mercaptobenzoxazole, phosphoric acid, acetic acid, and other solvents were obtained from commercial sources. These chemicals were used without further purification. 1-(4-(4-Hydroxy-3-tosylphenyl)piperazin-1-yl)ethanone (**13**) was synthesized according to a previously reported procedure.[15]

Electroorganic Synthesis of 7a,b and 12. A solution of phosphate buffer (60 mL; c = 0.2 M, pH = 2.0) in water/acetonitrile (45/15 v/v) solution, containing 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethanone (**1**) (0.25 mmol) and 2-*SH*-benzazoles (**2a,b**) (0.5 mmol), was electrolyzed in an undivided cell at 0.50 V vs SCE. The electrolysis was terminated when the current decreased by more than 95%. At the end of the electrolysis, the precipitated solid was collected by filtration and washed with water. The isolated yields of **7a,b** are reported in Scheme 1. For electrochemical synthesis of **12**, a solution of phosphate buffer (ca. 60 mL; c = 0.2 M, pH = 2.0) in water/acetonitrile (50/50 v/v) solution, containing **7a** (0.22 mmol) and **9** (0.22 mmol), was electrolyzed in an undivided cell at 0.60 V vs SCE. The electrolysis was terminated when the current decreased by more than 95%. At the end of the electrolysis, the precipitated solid was collected by filtration and washed with water.

*1-(4-(3,5-Bis(benzo[d]thiazol-2-ylthio)-4-hydroxyphenyl)-piperazin-1-yl)ethanone ($C_{26}H_{22}N_4O_2S_4$) (**7a**).* Mp: 96–98 °C dec. ^{1}H NMR (400 MHz $CDCl_3$): δ = 2.16 (s, 3H, methyl), 3.16 (t, 4H, aliphatic), 3.67 (t, 2H, aliphatic), 3.82 (t, 2H, aliphatic), 7.35 (m, 2H, aromatic), 7.44 (m, 4H, aromatic), 7.73 (d, J = 8.1 Hz, 2H), 7.85 (d, J = 8.1 Hz, 2H), 9.51 (broad, 1H, OH). ^{13}C NMR (100 MHz, DMSO-d_6): δ = 21.4, 41.2, 46.1, 50.1, 50.3, 111.7, 119.8, 121.0, 121.5, 122.1, 124.9, 126.5, 127.1, 135.5, 145.5, 152.9, 153.2, 167.4, 169.1. $IR_{(KBr)}$: 726.4, 756.3, 1006.1, 1080.1, 1155.9, 1235.0, 1425.4, 1455.7, 1620.2, 3424.3 cm^{-1}. MS: m/z (relative intensity) = 550 $[M]^+$ (1.6), 538 (2.4), 524 (3.2), 440 (39.7), 423 (3.2), 385 (31.7), 368 (40.5), 323 (19.8), 313 (34.1), 300 (100), 242 (89.7). Anal. Calcd for

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$C_{26}H_{22}N_4O_2S_4$: C, 56.70; H, 4.03; N, 10.17; S, 23.29. Found: C, 56.41; H, 4.02; N, 9.94; S, 23.38.

*1-(4-(3,5-Bis(benzo[d]oxazol-2-ylthio)-4-hydroxyphenyl)-piperazin-1-yl)ethanone ($C_{26}H_{22}N_4O_4S_2$) (**7b**).* Mp: 113−115 °C dec. ^{1}H NMR (400 MHz $CDCl_3$): δ = 2.16 (s, 3H, methyl), 3.11 (t, 2H, aliphatic), 3.17 (t, 2H, aliphatic), 3.63 (t, 2H, aliphatic), 3.78 (t, 2H, aliphatic), 7.31 (m, 4H, aromatic), 7.37 (s, 3H, aromatic), 7.47 (m, 2H, aromatic), 7.56 (m, 2H, aromatic), 9.12 (broad, 1H, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4, 41.3, 46.1, 50.0, 50.3, 110.1, 110.3, 117.5, 118.9, 123.7, 124.0, 124.8, 124.8, 126.5, 141.2, 151.7, 152.0, 162.9, 169.3. $IR_{(KBr)}$: 3424.1, 2908.8, 2822.7, 1624.0, 1571.6, 1496.1, 1472.0, 1452.4, 1363.5, 1320.1, 1281.9, 1164.8, 1132.5, 1001.7, 981.3, 927.4, 849.6, 805.8, 744.4, 623.9, 594.6, 422.7 cm^{-1} MS: *m*/*z* (relative intensity) = 518 $[M]^{+\bullet}$ (5.5), 484 (4.7), 397 (3.9), 367 (35.4), 324 (13.4), 297 (23.6), 259 (37.8), 242 (40.2), 226 (34.6), 175 (44.1), 151 (99.2), 91 (100). Anal. Calcd for $C_{26}H_{22}N_4O_4S_2$: C, 60.21; H, 4.28; N, 10.80; S, 12.34. Found: C, 60.51; H, 4.22; N, 10.39; S, 12.09.

*2-(Benzo[d]thiazol-2-ylthio)-6-tosylcyclohexa-2,5-diene-1,4-dione ($C_{20}H_{13}NO_4S_3$) (**12**).* Mp > 120 °C dec. MS: *m*/*z* (relative intensity) = 430 $[M + 3]^{+\bullet}$ (24), 402 (17.5), 338 (23.4), 284 (21), 171 (100), 128 (15.8), 95 (25.2).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

FT-IR, ^{1}H, ^{13}C NMR, and NOESY spectra for compounds **7a** and **7b**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Bondock, S.; Fadaly, W.; Metwally, M. A. *Eur. J. Med. Chem.* **2009**, *44*, 4813−4818.
(2) Akhtar, T.; Hameed, S.; Al-Masoudi, N. A.; Loddo, R.; La Colla, P. *Acta Pharm.* **2008**, *58*, 135−149.
(3) Leong, C. O.; Suggitt, M.; Swaine, D. J.; Bibby, M. C.; Stevens, M. F. G.; Bradshaw, T. D. *Mol. Cancer Ther.* **2004**, *3*, 1565−1575.
(4) Bradshaw, T. D.; Westwell, A. D. *Curr. Med. Chem.* **2004**, *11*, 1241−1253.
(5) (a) Zhang, L.; Fan, J.; Vu, K.; Hong, K.; Le Brazidec, J. Y.; Shi, J.; Biamonte, M.; Busch, D. J.; Lough, R. E.; Grecko, R.; Ran, Y.; Sensintaffar, J. L.; Kamal, A.; Lundgren, K.; Burrows, F. J.; Mansfield, R.; Timony, G. A.; Ulm, E. H.; Kasibhatla, S. R.; Boehm, M. F. *J. Med. Chem.* **2006**, *49*, 5352−5362. (b) Murru, S.; Ghosh, H.; Sahoo, S. K.; Patel, B. K. *Org. Lett.* **2009**, *11*, 4254−4257.
(6) Berkheij, M. *Tetrahedron Lett.* **2005**, *46*, 2369−2371.
(7) Vacca, J. P.; Dorsey, B. D.; Schleif, W. A.; Levine, R. B. *J. Med. Chem.* **1994**, *37*, 3443−3451.
(8) Choudhary, P.; Kumar, R.; Verma, K. *Bioorg. Med. Chem.* **2006**, *14*, 1819−1826.
(9) Upadhayaya, P. S.; Sinha, N.; Jain, S. *Bioorg. Med. Chem.* **2004**, *12*, 2225−2238.
(10) Hulme, C.; Cherrier, M. P. *Tetrahedron Lett.* **1999**, *40*, 5295−5299.
(11) Schiaffella, F.; Macchiarulo, A.; Milanese, L.; Vecchiarelli, A.; Fringuelli, R. *Bioorg. Med. Chem.* **2006**, *14*, 5196−5203.
(12) Blum, R, H.; Carter, S. K. *Ann. Intern. Med.* **1974**, *80*, 249−259.
(13) Huang, Z. D.; Chen, Y. N.; Menon, K.; Teicher, B. A. *J. Med. Chem.* **1993**, *36*, 1797−1801.
(14) Bittner, S.; Meenakshi, C.; Temtsin, G. *Tetrahedron* **2001**, *57*, 7423−7429.
(15) Nematollahi, D.; Amani, A. *J. Electroanal. Chem.* **2011**, *651*, 72−79.
(16) Nematollahi, D.; Khazalpour, S.; Amani, A. *J. Electrochem. Soc.* **2012**, *159*, E82−E86.
(17) Nematollahi, D.; Tammari, E. *J. Org. Chem.* **2005**, *70*, 7769−7772.
(18) Berlich, A.; Flemmig, B.; Wittstock, G. *J. Solid State Electrochem.* **2001**, *6*, 29−38.
(19) Bard, A. J.; Faulkner, L. R. *Electrochemical Methods*, 2nd ed.; Wiley: New York, 2001; p 472.
(20) Nematollahi, D.; Dehdashtian, S.; Niazi, A. *J. Electroanal. Chem.* **2008**, *616*, 79−86.