JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

COMMUNICATION

pubs.acs.org/JACS

Hydrogen Peroxide Inducible DNA Cross-Linking Agents: Targeted Anticancer Prodrugs

Yunyan Kuang,[†,‡] Kumudha Balakrishnan,[§] Varsha Gandhi,[§] and Xiaohua Peng*[,†]

[†]Department of Chemistry and Biochemistry, University of Wisconsin—Milwaukee, 3210 North Cramer Street, Milwaukee, Wisconsin 53211, United States

[‡]Department of Chemistry, Fudan University, 220 Handan Road, Shanghai City, 200433, China

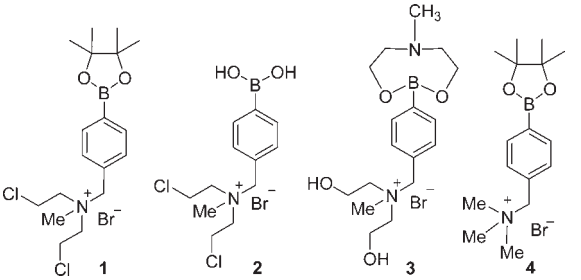
[§]Department of Experimental Therapeutics, MD Anderson Cancer Center, Houston, Texas 77030, United States

Supporting Information

ABSTRACT: The major concern for anticancer chemotherapeutic agents is the host toxicity. The development of anticancer prodrugs targeting the unique biochemical alterations in cancer cells is an attractive approach to achieve therapeutic activity and selectivity. We designed and synthesized a new type of nitrogen mustard prodrug that can be activated by high level of reactive oxygen species (ROS) found in cancer cells to release the active chemotherapy agent. The activation mechanism was determined by NMR analysis. The activity and selectivity of these prodrugs toward ROS was determined by measuring DNA interstrand cross-links and/or DNA alkylations. These compounds showed 60−90% inhibition toward various cancer cells, while normal lymphocytes were not affected. To the best of our knowledge, this is the first example of H_2O_2-activated anticancer prodrugs.

DNA interstrand cross-links (ICLs) are deleterious to cells, because they are unyielding obstruction to replication and transcription.[1] This property is exploited in cancer chemotherapy. ICL-inducing agents such as nitrogen mustards and cisplatin are among the most frequently used antitumor agents in the clinic. However, these agents exhibit severe host toxicity due to their poor selectivity toward cancer cells. One approach to reduce the toxicity of cross-linking agents for normal cells is to trigger the prodrug in tumor cells. Over the past few decades, several research groups have developed novel DNA cross-linking or alkylating agents that can induce ICL formation either by oxidation, reduction, or photolysis.[2−4] However, there is considerable scope for developing selective agents that can induce DNA cross-links specifically under tumor-specific conditions. It is believed that the estrogen receptor (ER) is overexpressed in many human breast and ovarian tumors. Essigmann and co-workers have developed tumor-specific toxins by conjugating an ER ligand with a DNA damaging nitrogen mustard or a bifunctional platinum(II) complex to achieve the selective killing of tumor cells while minimizing toxicity to normal tissues.[5] Cancer cells are also known to exhibit elevated intrinsic oxidative stress.[6−9] The increased amounts of reactive oxygen species (ROS) can be a therapeutic advantage, because it is an exclusive feature of cancer cells.[9] Therefore, it is of great interest to develop cross-linking agents that can be activated by ROS found in tumor cells and induce deleterious DNA damages (e.g., ICL formation or alkylation).

The most common ROS include hydrogen peroxide (H_2O_2), superoxide anions (O_2^-), and hydroxyl radical. Among these, H_2O_2 has the chemical stability required to establish significant steady-state concentrations in vivo and is uncharged. Compared with their normal counterparts, cancer cells have increased level of H_2O_2 (up to 0.5 nmol/10^4 cells/h).[6,10] These factors make H_2O_2 an ideal candidate as a therapeutic target for the development of ROS-activated prodrugs. Such agents should consist of two separate functional domains: a H_2O_2-accepting moiety ('trigger') and an 'effector', joined by a linker system in such a way that the reaction of the trigger with H_2O_2 causes a large increase in the cytotoxic potency of the effector. The aryl boronic acids and their esters are well-known to be cleaved by H_2O_2.[11] This reactivity provides a chemospecific, biologically compatible reaction method for detecting endogenous H_2O_2 production. Chang's group has used boronic esters for the development of H_2O_2-activated fluorescent probes for imaging H_2O_2 in cells.[12] Boronic acids and esters do not appear to have intrinsic toxicity issues, and the end product, boric acid, is considered nontoxic to humans.[13] All of this information encouraged us to use aryboronates or boronic acids as the trigger units for the development of H_2O_2-activated anticancer prodrugs. We chose nitrogen mustard as the effector to create a more broadly applicable strategy. Therefore, we designed and synthesized prodrugs of nitrogen mustards (**1** and **2**), investigated their inducible reactivities, and compared these activities with their analogues **3** and **4**.

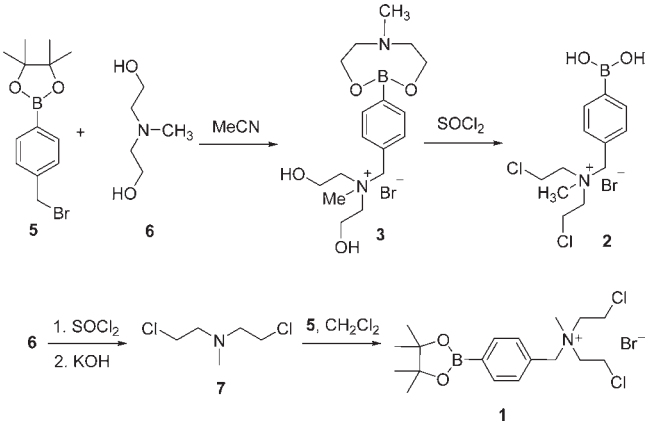


Compounds **1**−**3** were synthesized starting from 4-(bromomethyl)phenylboronic acid pinacol ester (**5**) (Scheme 1). Treatment of **5** with *N*-methyldiethanolamine yielded **3**, which was converted to **2** by using thionyl chloride. Compound **1** was prepared by the reaction of **5** with *N*,*N*-bis(2-chloroethyl)-methyl ammine (**7**, HN2). In a similar way, **4** was synthesized (Supporting Information (SI), Scheme S2).

Received: August 10, 2011
Published: October 28, 2011

dx.doi.org/10.1021/ja2073824 | *J. Am. Chem. Soc.* 2011, 133, 19278–19281

Scheme 1. The Synthesis of 1−3



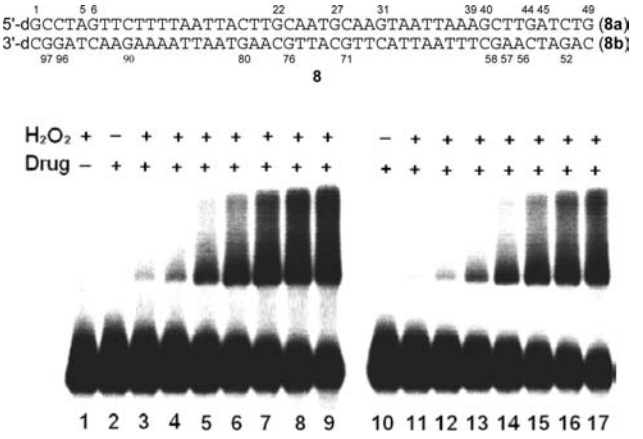


Figure 1. Concentration dependence of compounds **1** and **2** for DNA cross-link formation upon H_2O_2-activation. Lane 1 without drug; lanes 2−9 with drug **1**: lane 2, without H_2O_2 (cross-linking yield 0%); lane 3, 50 μM H_2O_2 + 100 μM **1** (2.2%); lane 4, 100 μM H_2O_2 + 200 μM **1** (5%); lane 5, 250 μM H_2O_2 + 500 μM **1** (11%); lane 6, 500 μM H_2O_2 + 1.0 mM **1** (18%); lane 7, 1.0 mM H_2O_2 + 2.0 mM **1** (28%); lane 8, 1.5 mM H_2O_2 + 3.0 mM **1** (36%); lane 9, 2.0 mM H_2O_2 + 4.0 mM **1** (42%); lanes 10−17 with drug **2**: lane 10, without H_2O_2 (0%); lane 11, 50 μM H_2O_2 + 100 μM **2** (2.0%); lane 12, 100 μM H_2O_2 + 200 μM **2** (4%); lane 13, 250 μM H_2O_2 + 500 μM **2** (11%); lane 14, 500 μM H_2O_2 + 1.0 mM **2** (17%); lane 15, 1.0 mM H_2O_2 + 2.0 mM **2** (27%); lane 16, 1.5 mM H_2O_2 + 3.0 mM **2** (35%); lane 17, 2.0 mM H_2O_2 + 4.0 mM **2** (43%).

It was known that the ICLs are the source of the cytotoxicity of nitrogen mustards. Thus, the activity of **1** and **2** was investigated by determining their ability to form DNA interstrand cross-links using a 49-mer DNA duplex **8**. The DNA cross-linking experiments were carried out in phosphate buffer (pH = 7.5). ICL formation and cross-linking yield were analyzed via denaturing polyacrylamide gel electrophoresis (PAGE) with phosphorimager analysis (Image Quant 5.2) by taking advantage of the differing mobilities of ICL products and single stranded DNA. In the absence of H_2O_2, no ICL was observed with **1** and **2** (Figure 1, lanes 2 and 10), which indicates the toxicity of nitrogen mustard mechlorethamine (**7**) is masked in the prodrugs. When **8** was treated with **1** or **2** in the presence of H_2O_2, efficient cross-link formation was observed (11−43%) (Figure 1, lanes 5−9 and 13−17). DNA cross-linking by **1** and **2** was observed at a

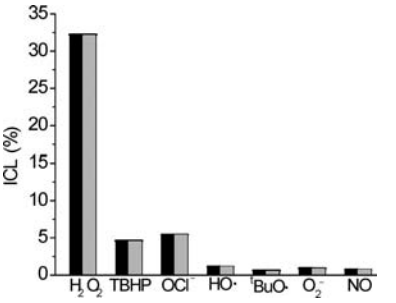


Figure 2. ICL formation induced by **1** and **2** (2 mM) upon treatment with various ROS at 1 mM (black bar, compound **1**; gray bar, compound **2**).

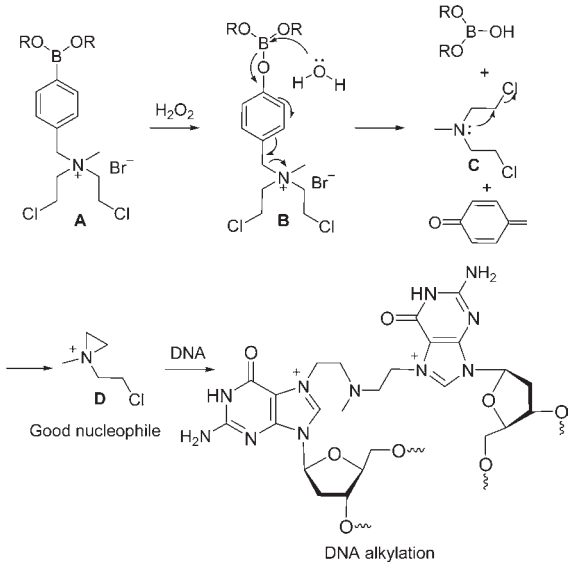
concentration of H_2O_2 as low as 50 μM (lanes 3 and 11). This clearly shows that **1** and **2** are nontoxic to DNA, but can be activated by H_2O_2 to release the DNA damaging agent **7**. The best ratio of drug to H_2O_2 is 2:1 (SI, Figure S1). ICL growth followed first-order kinetics. The observed rate constant for ICL formation induced by **1** (k_{ICL} = (4.6 ± 0.4) × 10^{-5} s^{-1}, $t_{1/2}$ = 4.2 h) was within experimental error of that induced by **2** (k_{ICL} = (4.7 ± 0.3) × 10^{-5} s^{-1}, $t_{1/2}$ = 4.1 h) (SI, Figure S2).

As H_2O_2 is not the only ROS in biological system, we studied the inducible activity of **1** and **2** toward other ROS, such as *tert*-butylhydroperoxide (TBHP), hypochlorite (OCl^-), hydroxyl radical, *tert*-butoxy radical, superoxide ($O_2^{\cdot-}$), and nitric oxide. The activation of **1** and **2** to release nitrogen mustard is highly selective for H_2O_2 over other ROS, which is demonstrated by the selective ICL formation (Figure 2 and SI, Figure S3). In the presence of H_2O_2, compounds **1** and **2** induced efficient ICL formation (35%), while less than 5% ICLs were observed with other ROS. The selective reaction of phenylboronate or boronic acid derivatives (**1** and **2**) with H_2O_2 is consistent with the observation of Chang's group.[12e]

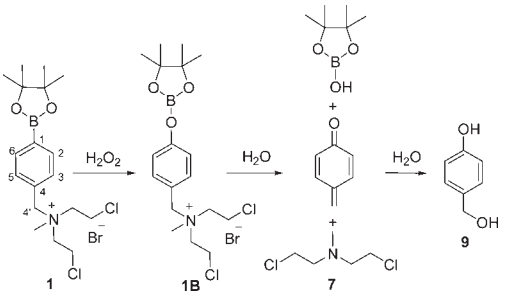
To provide further insight into the reactivity of **1** and **2**, we examined the stability and reactivity of purified ICL products and single-stranded DNA isolated from the reaction mixture (**8a**′ and **8b**′). The stability of DNA alkylation products depends upon the reaction site. The cross-links formed from **1** and **2** were almost completely destroyed upon heating at 90 °C (pH 7.2) for 30 min (SI, Figrue S4). When the ICL was treated with 1 M piperidine (90 °C, 30 min), strong DNA cleavage bands were observed with all dGs and weaker bands with dAs (SI, Figures S5 and S6). These results are consistent with the reaction of nitrogen mustard mainly occurring at N7- of dG.[14] The alkaline hydrolysis of N7-alkylated purines produces formamidopyrimidines that are labile to heating in piperidine.[2c,15] It was reported that nitrogen mustard forms ICLs in 5′-dGC or 5′-dGNC sequences.[14] Therefore, the possible cross-linking sites are G1−G97, G22−G76, G27−G71, G40−G58, or G1−G96, G49−G52 (SI, Figrue S5, lanes 4, 8, 14, 20). The alkylation was also observed with all DNA guanine units in single-stranded DNA **8a**′ and **8b**′ (SI, Figure S5, lanes 3, 7, 13, 19). In a control experiment, **8** was treated with drug alone (**1** or **2**) or H_2O_2 alone, and no cleavage band was observed (SI, Figure S5, lanes 1, 2, 11, 12, 17, 18). This indicated that **1**, **2**, or H_2O_2 alone do not induce DNA damage under the conditions used in our experiments. When duplex **8** was treated with **3** or **4** in the presence of H_2O_2 followed by 1 M piperidine (90 °C, 30 min), there was no DNA cleavage band observed (SI, Figure S7). These data showed that the released quinone methide by **3** or **4** did not produce detectable DNA alkylations under our experimental conditions. Rokita et al. has shown that

dx.doi.org/10.1021/ja2073824 |*J. Am. Chem. Soc.* 2011, 133, 19278–19281

Scheme 2. ICL Formation Induced by 1 and 2 upon H_2O_2-Activation



Scheme 3. Release of Nitrogen Mustard by 1 upon Treatment with H_2O_2



adducts formed between quinone methides and deoxynucleosides were reversible, and the labile alkylating products tended to decompose with short half-life time and were difficult to be isolated.[16] Therefore, the detected ICL formation or alkylation induced by **1** or **2** in the presence of H_2O_2 was exclusively induced by **7** released from **1** and **2**. In a control experiment, we examined the cross-linking efficiency of nitrogen mustard **7** alone (47% ICLs), which was identical to those induced by **1** and **2** (43%) upon H_2O_2-activation (SI, Figure S8).

The masked toxicity of nitrogen mustard in **1** and **2** was caused by the positive charge developed on the nitrogen (**A**) that strongly decreases the electron density of mustard nitrogen required for alkylation (Scheme 2). The release of tertiary amine **C** is triggered by the oxidation of the carbon−boron bond initiated by nucleophilic attack by H_2O_2 (**A** → **B**), followed by deboronation (**B** → **C**) . The lone pair developed on **C** can form highly electrophilic aziridinium ring **D** by intramolecular displacement of the chloride by the amine nitrogen. **D** greatly facilitates the DNA alkylation and cross-linking formation. The activation of **1** and **2** by H_2O_2 (**A** → **B**) and the release of **C** were further confirmed by NMR analysis of the reaction of **1** and **2** with H_2O_2.

Initially, the reaction of **1** and **2** with H_2O_2 was performed in 10 mM deuterated potassium phosphate buffer (pH 7.5). However, the reaction was too fast to observe all intermediates. Compound **1** was oxidized by 97% within 5 min and spontaneously released **7** (SI, Figure S9B). After 2 h, **1** was completely consumed and converted to **7** (SI, Figure S9C). Similarly, the activation of **2** with H_2O_2 followed by the release of **7** was complete within 2 h (SI, Figure S9D−F). When the reaction of **1** with H_2O_2 was carried out in a mixture of DMSO/D_2O, we were able to observe all intermediates (Scheme 3 and Figure 3). The integral change of C_2−H, C_3−H, and $C_{4'}$−H indicated the kinetic transformation of compound **1** into nitrogen mustard **7**. Compound **1** was transformed to **1B** by 5% after 2 h (Figure 3A), as evidenced by the presence of δ 7.35 (doublet), δ 6.83 (doublet), and δ 4.53 (singlet). Subsequently, 1,6-benzyl elimination of **1B** took place leading to quinone methide that

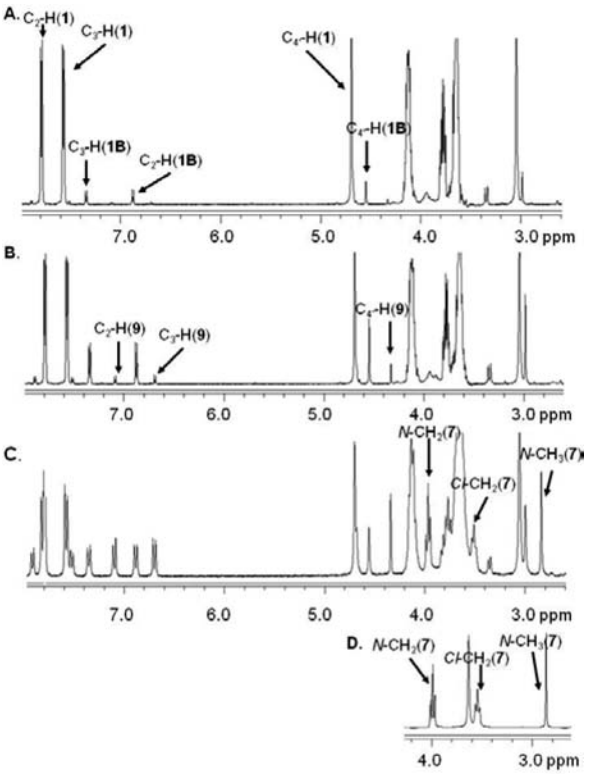


Figure 3. ^{1}H NMR analysis of the activation of **1** by H_2O_2 in a mixture of D_2O/DMSO: (A) 2 h after addition of H_2O_2 (1.5 equiv); (B) 5 h after addition of H_2O_2; (C) 24 h after addition of H_2O_2; (D) ^{1}H NMR of **7** in a mixture of D_2O/DMSO.

spontaneously reacted with H_2O. This was evidenced by the appearance of C_2−H (δ 7.09, doublet), C_3−H (δ 6.70), and $C_{4'}$−H (δ 4.33) of compound **9** (2% within 5 h) (Figure 3B). Compounds **1B** and **9** were obtained in 32% and 20% within 24 h (Figure 3C). Nitrogen mustard **7** was released in about 25%, as shown by the shift of δ 4.13 (multiplet) to δ 3.96 (triplet) and δ 3.06 (singlet) to δ 2.84 (singlet) (Figure 3C). These data are consistent with those of the authentic sample (Figure 3D). Compound **1** was activated by H_2O_2 to release nitrogen mustard **7** in approximate 95% yield within 4 days in DMSO/D_2O (SI, Figure S10B). However, NMR analysis 4 days after the addition of H_2O_2 to **2** did not show any change with compound **2** in DMSO/D_2O. It is highly likely that the weak acidity of

dx.doi.org/10.1021/ja2073824 |J. Am. Chem. Soc. 2011, 133, 19278–19281

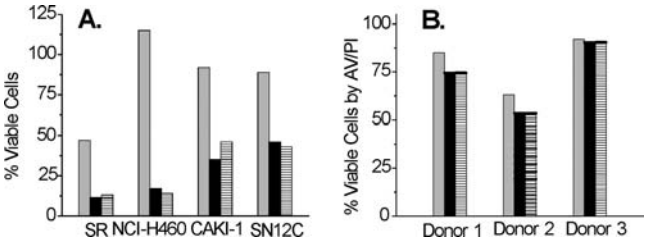


Figure 4. Effect of compounds **1**−**3** on cancer cells and normal lymphocytes: (A) four human cancer cells (SR, NCI-H460, CAKI-1, and SN12C)) were incubated with 10 μM of compounds **1**−**3** for 48 h (gray bar, **3**; black bar, **1**; lined bar, **2**); (B) normal lymphocytes obtained from healthy donors ($n = 3$) were incubated with 10 μM of **1** and **2** for 48 h. Time matched control samples are set up concurrently (gray bar, control; black bar, compound **1**; lined bar, compound **2**).

boronic acid group in **2** inhibits the oxidative ability of H_2O_2. It is precedented that the reaction between arylboronic acid and hydrogen peroxide was pH-dependent.[11,17]

Having established that the prodrugs **1** and **2** could be effectively passivated and activated by H_2O_2, the ability of these compounds to inhibit cancer cell growth was evaluated. Both compounds inhibited various types of cancer cells at 10 μM. They showed about 90% inhibition toward SR cells (Leukemia cell), 85% inhibition toward NCI-H460 (Nonsmall Cell Lung Cancer cells), and 66% inhibition toward CAKI-1, and 57% toward SN12C (Renal Cancer cells) (Figure 4A).[18] However, compound **3** is less toxic to these cells. The toxicity of **1** and **2** is highly likely caused by the release of nitrogen mustard after tumor-specific activation. To determine the selectivity, we evaluated the toxicity of **1** and **2** toward noncancer cells. Normal lymphocytes obtained from three healthy donors were incubated without or with 10 μM of compounds **1** and **2**; untreated samples were used as time-matched controls. In all the 3 samples studied, compared to time-matched controls, there was no increase in apoptosis observed at 24−72 h (Figure 4B and SI, Figure S11).

In conclusion, two prodrugs of nitrogen mustard coupled with an arylboronate or boronic acid demonstrated an effective way to mask the cytotoxicity of cancer chemotherapeutic agents and selectively release them in the presence of H_2O_2. The activity and selectivity were measured by cross-linking or alkylation of DNA as well as by evaluating their ability to inhibit cancer cell growth and toxicity toward normal cells. To the best of our knowledge, we are the first to report anticancer prodrugs (**1** and **2**) that can be activated by ROS to release DNA cross-linking agents. Such compounds are nontoxic but are highly likely to undergo tumor-specific activation to generate toxic species in cancer cell. They offer novel ways to improve the therapeutic effectiveness and selectivity of current anticancer agents.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures for all reaction and analyses, preparation and characterization of **1**−**7**, bioactive evaluation, autoradiograms of Fe·EDTA, and piperidine treatment of cross-linked products and reacted single-stranded DNA. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author
pengx@uwm.edu

■ ACKNOWLEDGMENT

We are grateful for financial support of this research from the National Cancer Institute (1R15CA152914-01) and UWM start-up funds (X.P.). This research was supported in part by the National Cancer Institute (-CA136411) Lymphoma SPORE (V.G.).

■ REFERENCES

(1) (a) Noll, D. M.; Mason, T. M.; Miller, P. S. *Chem. Rev.* **2006**, *106*, 277. (b) Dronkert, M. L. G.; Kanaar, R. *Mutat. Res.* **2001**, *486*, 217.

(2) (a) Hong, I. S.; Greenberg, M. M. *J. Am. Chem. Soc.* **2005**, *127*, 10510. (b) Hong, I. S.; Ding, H.; Greenberg, M. M. *J. Am. Chem. Soc.* **2006**, *128*, 485. (c) Peng, X.; Hong, I. S.; Li, H.; Seidman, M. M.; Greenberg, M. M. *J. Am. Chem. Soc.* **2008**, *130*, 10299.

(3) (a) Veldhuyzen, W. F.; Pande, P.; Rokita, S. E. *J. Am. Chem. Soc.* **2003**, *125*, 14005. (b) Richter, S. N.; Maggi, S.; Mels, S. C.; Palumbo, M.; Freccero, M. *J. Am. Chem. Soc.* **2004**, *126*, 13973. (c) Wang, H.; Rokita, S. E. *Angew. Chem., Int. Ed.* **2010**, *49*, 5957.

(4) (a) Wang, P.; Liu, R.; Wu, X.; Ma, H.; Cao, X.; Zhou, P.; Zhang, J.; Weng, X.; Zhang, X.; Qi, J.; Zhou, X.; Weng, L. *J. Am. Chem. Soc.* **2003**, *125*, 1116. (b) Weng, X.; Ren, L.; Weng, L.; Huang, J.; Zhu, S.; Zhou, X.; Weng, L. *Angew. Chem., Int. Ed.* **2007**, *46*, 8020.

(5) (a) Shawn, M. H.; Marquis, J. C.; Zayas, B.; Wishnok, J. S.; Liberman, R. G.; Skipper, P. L.; Tannenbaum, S. R.; Essigmann, J. M.; Croy, R. G. *Mol. Cancer Ther.* **2006**, *5*, 977. (b) Rink, S. M.; Yarema, K. J.; Solomon, M. S.; Paige, L. A.; Mitra Tadayoni-Rebek, B.; Essigmann, J. M.; Croy, R. G. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 15063. (c) Kim, E.; Rye, P. T.; Essigmann, J. M.; Croy, R. G. *J. Inorg. Biochem.* **2009**, *103*, 256.

(6) Szatrowski, T. P.; Nathan, C. F. *Cancer Res.* **1991**, *51*, 794.

(7) Toyokuni, S.; Okamoto, K.; Yodoi, J.; Hiai, H. *FEBS Lett.* **1995**, *358*, 1.

(8) Kawanishi, S.; Hiraku, Y.; Pinlaor, S.; Ma, N. *Biol. Chem.* **2006**, 365.

(9) (a) Pelicano, H.; Carney, D.; Huang, P. *Drug Resist. Updates* **2004**, *7*, 97. (b) Trachootham, D.; Alexandre, J.; Huang, P. *Nat. Rev.* **2009**, *8*, 579. (c) Lopez-Lazaro, M. *Cancer Lett.* **2007**, *252*, 1.

(10) (a) Zieba, M.; Suwalski, M.; Kwiatkowska, S.; Piasecka, G.; Grzelewska-Rzymowska, I.; Stolarek, R.; Nowak, D. *Respir. Med.* **2000**, *94*, 800. (b) Lim, S. D.; Sun, C.; Lambeth, J. D.; Marshall, F.; Amin, M.; Chung, L.; Petros, J. A.; Arnold, R. S. *Prostate* **2005**, *62*, 200.

(11) Kuivila, H. G.; Armour, A. G. *J. Am. Chem. Soc.* **1957**, *79*, 5659.

(12) (a) Miller, E. W.; Albers, A. E.; Pralle, A.; Isacoff, E. Y.; Chang, C. J. *J. Am. Chem. Soc.* **2005**, *127*, 16652. (b) Dickinson, B. C.; Chang, C. J. A. *J. Am. Chem. Soc.* **2008**, *130*, 9638. (c) Miller, E. W.; Tulyathan, O.; Isacoff, E. Y.; Chang, C. J. *Nat. Chem. Biol.* **2007**, *3*, 263. (d) Lo, L. C.; Chu, C. Y. *Chem. Commun.* **2003**, 2728. (e) Srikun, D.; Miller, E. W.; Domaille, D. W.; Chang, C. J. A. *J. Am. Chem. Soc.* **2008**, *130*, 4596.

(13) Yang, W. Q.; Gao, X.; Wang, B. H. In *Boronic Acids*; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2005; pp 481−512.

(14) (a) Brookes, P.; Lawley, P. D. *Biochem. J.* **1961**, *80*, 496. (b) Rink, S. M.; Solomon, M. S.; Taylor, M. J.; Rajur, S. B.; McLaughlin, L. W.; Hopkins, P. B. *J. Am. Chem. Soc.* **1993**, *115*, 2551. (c) Dong, Q.; Barsky, D.; Colvin, M. E.; Melius, C. F.; Ludeman, S. M.; Moravek, J. F.; Colvin, O. M.; Bigner, D. D.; Modrich, P. *Proc. Natl. Acad. Sci. U.S.A.* **1995**, *92*, 12170.

(15) Haraguchi, K.; Delaney, M. O.; Wiederholt, C. J.; Sambandam, A.; Hantosi, Z.; Greenberg, M. M. *J. Am. Chem. Soc.* **2002**, *124*, 3263.

(16) Weinert, E. E.; Dondi, R.; Colloredo-Melz, S.; Frankenfield, K. N.; Mitchell, C. H.; Freccero, M.; Rokita, S. E. *J. Am. Chem. Soc.* **2006**, *128*, 11940.

(17) Kuivila, H. G. *J. Am. Chem. Soc.* **1954**, *76*, 870.

(18) Data were obtained from Developmental Therapeutics Program at the National Cancer Institute (NCI-60 DTP Human Tumor Cell Line Screen).