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# Discovery and Characterization of 2-Anilino-4-(Thiazol-5-yl)Pyrimidine Transcriptional CDK Inhibitors as Anticancer Agents

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## SUMMARY

**The main difficulty in the development of ATP antagonist kinase inhibitors is target specificity, since the ATP-binding motif is present in many proteins. We introduce a strategy that has allowed us to identify compounds from a kinase inhibitor library that block the cyclin-dependent kinases responsible for regulating transcription, i.e., CDK7 and especially CDK9. The screening cascade employs cellular phenotypic assays based on mitotic index and nuclear p53 protein accumulation. This permitted us to classify compounds into transcriptional, cell cycle, and mitotic inhibitor groups. We describe the characterization of the transcriptional inhibitor class in terms of kinase inhibition profile, cellular mode of action, and selectivity for transformed cells. A structural selectivity rationale was used to optimize potency and biopharmaceutical properties and led to the development of a transcriptional inhibitor, 3,4-dimethyl-5-[2-(4-piperazin-1-yl-phenylamino)-pyrimidin-4-yl]-3*H*-thiazol-2-one, with anticancer activity in animal models.**

## INTRODUCTION

Cyclin-dependent kinases (CDKs) are key cell cycle regulators and some also have regulatory functions in mRNA transcription at the level of RNA polymerase-II (RNAP-II) (Hirose and Ohkuma, 2007). CDKs 1, 2, 7, 8, 9, and 11 have all been implicated in the phosphorylation of the C-terminal domain (CTD) of the largest RNAP-II subunit (Pinhero et al., 2004), but the most important ones are CDK7-cyclin H and CDK9-cyclin T (Ramanathan et al., 2001). The CTD contains repeating Tyr-Ser-Pro-Thr-Ser-Pro-Ser heptad sequences and the phosphorylation status of the Ser residues at positions 2 and 5 has been shown to be important in the activation of RNAP-II.

CDK7-cyclin H associates with the RING-finger protein MAT1 in the general transcription factor IIH (TFIIH) and also acts as an activating kinase for other CDKs. Unlike other CDKs, CDK9 appears to function exclusively in transcriptional regulation. It forms complexes with cyclin T1, T2, or K, which participate in the positive transcription elongation factor b (P-TEFb) (Michels et al., 2003). CDK9 phosphorylates both Ser-2 and Ser-5 of the CTD heptad (Pinhero et al., 2004), playing a predominant role during transcriptional elongation, in contrast to CDK7, which primarily phosphorylates Ser-5 of RNAP-II at the promoter as part of transcriptional initiation (Gomes et al., 2006).

Overexpression of cyclins or suppression of CDK-inhibitory proteins (CDKIs) is frequently observed in cancers and ectopic expression of CDKIs in tumor cells restores cell cycle control, leading to cell cycle arrest or apoptosis (Shapiro and Harper, 1999). However, it is now clear that many CDKs and cyclins associated with the cell cycle are functionally redundant, which suggests that targeting individual cell cycle CDKs may not be an optimal therapeutic strategy (Barriere et al., 2007). The anticancer activity in preclinical models of the experimental CDK inhibitor drugs flavopiridol (alvocidib; Aventis/NCI) and *R*-roscovitine (seliciclib, CYC202; Cyclacel) are believed to result mostly from the transcriptional inhibition mechanism (Fischer and Gianella-Borradori, 2005). Flavopiridol targets a number of CDKs and other kinases, and transcription inhibition caused by this compound in cancer cells was originally thought to be mediated by inhibition of CDK7 (Harper and Elledge, 1998). Recent data, however, suggest that CDK9 inhibition plays a more important role (Chen et al., 2005). Treatment of cancer cells with flavopiridol results in inhibition of RNAP-II CTD phosphorylation, thus blocking transcription and inducing apoptosis by reducing mRNA levels of antiapoptotic proteins (Gojo et al., 2002). Selective induction of apoptosis in transformed cells by downregulation of antiapoptotic proteins through transcriptional CDK inhibition has also been demonstrated for *R*-roscovitine (MacCallum et al., 2005).

Clinical trials results show flavopiridol monotherapy efficacy in hematological cancers, especially chronic lymphocytic leukemia, which is particularly sensitive to transcriptional inhibition (Byrd et al., 2007). Many clinical and preclinical pan-CDK inhibitor compounds are potent CDK9 inhibitors and their antiproliferative properties emanate from transcriptional inhibition to a large extent (Joshi et al., 2007; Karaman et al., 2008;

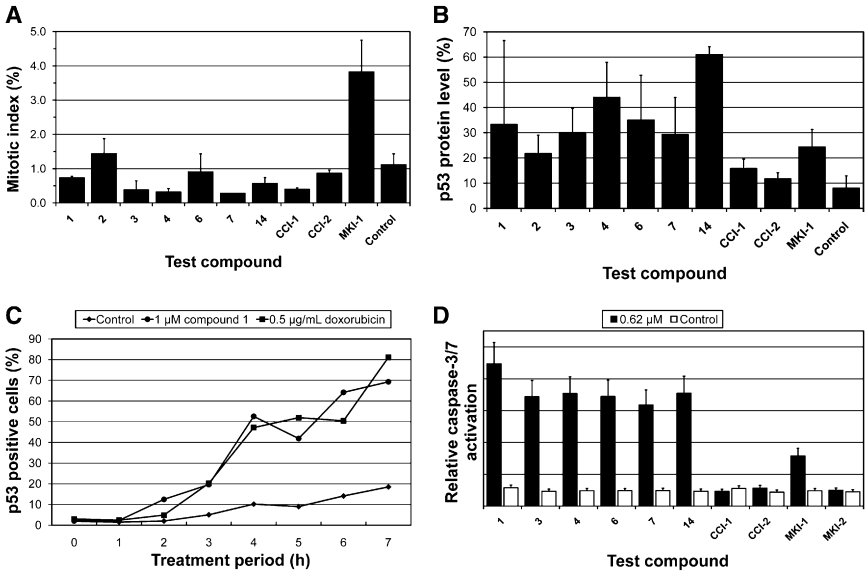



**Figure 1. Identification of CDK Transcriptional Inhibitors by Cell-Based Assays in A2780 Cancer Cells**

Cells were treated with test compounds or assay diluent only (control) at 0.63 μM (A, B) or the concentrations indicated (C) for 7 hr (A–C) or 24 hr (D). MI was measured by determining the percentages of phospho-histone-H3 positive cells (A). Nuclear accumulation of p53 was assessed by immunofluorescent staining (B). Transcription inhibitors induce a time-dependent increase in p53 protein (C) and an apoptotic signal through activation of caspases-3/7 (D). See also Figures S1. Data are represented as mean ± SD.

Wang and Fischer, 2008; Zhang et al., 2008). However, truly CDK7- and CDK9-selective compounds have not been reported to date (Wang and Fischer, 2008).

Here, we report the results that have led to the identification of potent and selective new pharmacological CDK transcriptional inhibitors from our 2-anilino-4-(heteroaryl)-pyrimidine kinase inhibitor compound library (Wang et al., 2004a, 2004b; Wu et al., 2003). We have developed a cell-based screening cascade that has enabled us effectively to delineate a pharmacophore subseries of compounds characterized by selective antiproliferative effects in tumor cells through transcriptional CDK inhibition. This cascade has permitted us to distinguish phenotypically and biochemically compounds that inhibit RNAP-II CDKs from those that act predominantly through inhibition of the cell cycle CDKs (1, 2, 4), or the closely related mitotic aurora kinases. We use assays for mitotic index (MI), and p53 protein level measurements as a proxy measure for general transcriptional inhibition, for initial mechanistic compound classification, followed by more specific cell biological screens, such as caspase-3/7 activation assays, for more detailed compound mode-of-action analysis and classification (Griffiths et al., 2004, 2008; Wang et al., 2004a, 2005).

## RESULTS

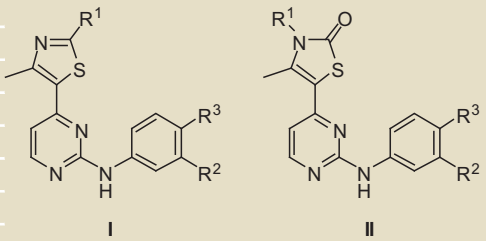
### Cellular Phenotypic Classification

The effects of treatment of A2780 (ovarian), NCI-H460 (non-small cell lung), and A549 (lung) tumor cell lines with compounds from our kinase inhibitor library were assessed using high-throughput cell biological assays based on an automated microscopy system. Among these, MI and p53 protein level assays were found to be the most informative for classification of the library subgroups that target the cell cycle or transcription, respectively. Based on time-course experiments, a 7 hr treatment period with test compounds was chosen to identify maximum effects on cell cycle or induction of p53 protein levels. p53 expression is regulated at the level of protein stability, and the increase in p53 protein levels after treatment with transcriptional inhibitors, including flavopiridol, is attributed to the downregulation of Mdm2 (Demidenko and Blagosklonny, 2004; Lu et al., 2001; Radhakrishnan and Gartel, 2006), which is a well-established negative regulator of p53 protein (Michael and Oren, 2003). Compounds were typically screened using a concentration range of 0.04–20 μM, which permitted assessment of both potency and phenotypic specificity. Examination of MI and p53 protein levels resulted in identification of three classes of compounds: class-1 compounds decreased MI and induced high levels of nuclear p53 protein; class-2 compounds increased MI, but had minimal effects on p53 protein levels; and class-3 compounds decreased MI and had minimal effects on p53 levels. Representatives of each class of compounds were further evaluated by enzymatic screening and cellular mode-of-action investigations.

MI was used as an indicator of cell cycle status in unsynchronized proliferating cells. Figure 1A illustrates the response of A2780 cells and is representative across the concentration range (the results from a primary MI and p53 screen of a set of 220 compounds is shown in Figure S1A, available online). Class-2 compounds, exemplified by a compound we have designated MKI-1 (for mitotic kinase inhibitor), delayed cells in mitosis and increased the overall MI of the cell population. Many of these compounds were subsequently identified as selective inhibitors of aurora kinases (data not shown; Wang et al., 2010). Class-1 compounds such as **1**, **3**, **4**, **6**, **7**, and **14** (Table 1) decreased MI, indicating a reduction in the number of cycling cells (Figure 1A) and increased the number of cells with high levels of nuclear accumulation of p53, typically with a 3- to 6-fold increase in A2780 (Figure 1B). To determine if p53 induction was a result of a DNA damage response (Kastan et al., 1991), additional experiments were carried out using an independent DNA-damage response marker, phosphorylated histone H2AX (Rogakou et al., 1998). Treatment of MCF-7 cells with either doxorubicin, a classical DNA-damaging agent (Gewirtz, 1999), or **1** resulted in accumulation of p53 (Figure 1c). Treatment with **1** had no effect on the level of histone H2AX phosphorylation, which was increased substantially by doxorubicin (Figure S1B). A likely mechanism of p53 accumulation for class-1 compounds is reduction in the transcription and expression of Mdm2, the ubiquitin ligase responsible for degradation of

**Table 1. Structures and Biological Activity of Selected CDK Inhibitors**

| No. | Structure Formula | $R^1$ | $R^2$ | $R^3$ |
|---|---|---|---|---|
| **1** | I | $NH_2$ | $NO_2$ | H |
| **2** | I | NHEt | $SO_2NH_2$ | H |
| **3** | I | NHMe | $SO_2NH_2$ | H |
| **4** | I | NHMe | $SO_2NHMe$ | H |
| **5** | I | $NH_2$ | $SO_2NHMe$ | H |
| **6** | I | NHMe | $SO_2Me$ | H |
| **7** | I | NHEt | $SO_2Me$ | H |
| **8** | I | $NH_2$ | $SO_2NHEt$ | H |
| **9** | I | NHMe | $SO_2$-morpholine | Me |
| **10** | I | $NH_2$ | $SO_2$-morpholine | Me |
| **11** | II | Me | H | $SO_2NH(CH_2)_2OMe$ |
| **12** | II | Me | CN | H |
| **13** | II | Me | $NO_2$ | Me |
| **14** | II | Me | H | Piperazine |




| No. | Kinase inhibition, $K_i$ (nM) | | | | | 72 hr MTT, $IC_{50}$ (nM) | |
|---|---|---|---|---|---|---|---|
| | *CDK1* | *CDK2* | *CDK4* | *CDK7* | *CDK9* | *A2780* | *MES-SA* |
| **1** | 73±31 | <1 | 19±17 | 73±5 | 4.6±5.2 | 41±2 | 140±13 |
| **2** | 691±81 | 403±29 | 132±53 | 56±24 | 4.5±1.4 | 666±106 | 1608±235 |
| **3** | 67±11 | 2.4±1.3 | 9.1±2.9 | 25±7 | 0.80±0.79 | 12±5 | 76±10 |
| **4** | 334±3 | 33±1 | 20±7 | 107±71 | 4.3±2.1 | 178±44 | 278±75 |
| **5** | 233±32 | 26±3 | 163±73 | 127±48 | 4.3±1.8 | 205±156 | 428±45 |
| **6** | 86±63 | 1.6±0.2 | 94±4 | 91±13 | 0.29±0.27 | 87±2 | 93±15 |
| **7** | >500 | 7.6±1.5 | 139±23 | 47±24 | 0.96±0.14 | 101±2 | 50±15 |
| **8** | 660±353 | 47±16 | 391±50 | 193±13 | 5.9±1.5 | 332±13 | 425±65 |
| **9** | >500 | >500 | >500 | 3,469±1,526 | 6.7±3.0 | 760±336 | 370±43 |
| **10** | >500 | >500 | >500 | 304±87 | 8.5±1.3 | 692±35 | 169±45 |
| **11** | 4.1±0.8 | 0.11±0.05 | >500 | 940±55 | 14±2 | 221±75 | 98±10 |
| **12** | 399±16 | 0.52±0.11 | 102±53 | 6.8±3.0 | 1.9±2.3 | 216±20 | 367±30 |
| **13** | 3.0±0.5 | 28±3 | 60±18 | 0.56±0.13 | 5.9±3.3 | 34±1 | 126±30 |
| **14** | 449±48 | 149±40 | 68±28 | 2.3±0.2 | 0.38±0.27 | 131±9 | 150±16 |

See also Table S1. Data are represented as mean ± SD.

p53 (Lu et al., 2001). Direct evidence for this mechanism was obtained after detailed investigations with compound **14** (see below). Nuclear p53 protein levels were subsequently used as an indicator of general transcriptional inhibition and this correlated well with biochemical selectivity for CDK 7 and 9 inhibition (Figure 2).

The third class of inhibitors, exemplified by the compounds designated CCI-1 and CCI-2 (for cell-cycle inhibitors) in Figures 1A and 1B, reduced MI but had no significant effect on p53 protein levels. These compounds were subsequently identified as selective cell cycle inhibitors, which cause stage-specific cell cycle arrest and prevent mitotic entry (Wang et al., 2005).

## CDK Transcriptional Inhibitors Induce Apoptosis in Tumor Cells

Caspases 3 and 7 are the most crucial effector components of cell death pathways that culminate in the cleavage of a number of important cellular proteins (Fuentes-Prior and Salvesen, 2004). We found that all of the compounds that we had identified as transcriptional CDK inhibitors (class-1) were capable of inducing a caspase-3/7 response in tumor cell lines, including A2780, NCI-H460, MES-SA (uterine sarcoma), and HT-29 (colon adenocarcinoma). When, e.g., A2780 cells were treated with **1**, **3**, **4**, **6**, **7**, and **14** for 24 hr, substantial induction of apoptosis was observed, typically a >7-fold induction of caspase-3/7 activation, compared with class-2 (MKI-1 and 2) and class-3 compounds (CCI-1 and 2), or controls (Figure 1D). Caspase activation was only observed in transformed lines and not in the nontransformed fetal lung cell line WI-38, despite it being able to activate caspases 3/7 in response to other classes of compounds. In all cases, full induction of caspase activity occurred over a narrow concentration range as an all-or-nothing response (Figure 3A). Selective induction of apoptosis in transformed lines was confirmed by TUNEL of A2780 and WI-38 cells treated with compound **14**. Cell-cycle arrest was not detected, and TUNEL-positive cells originated from all stages of the cell cycle

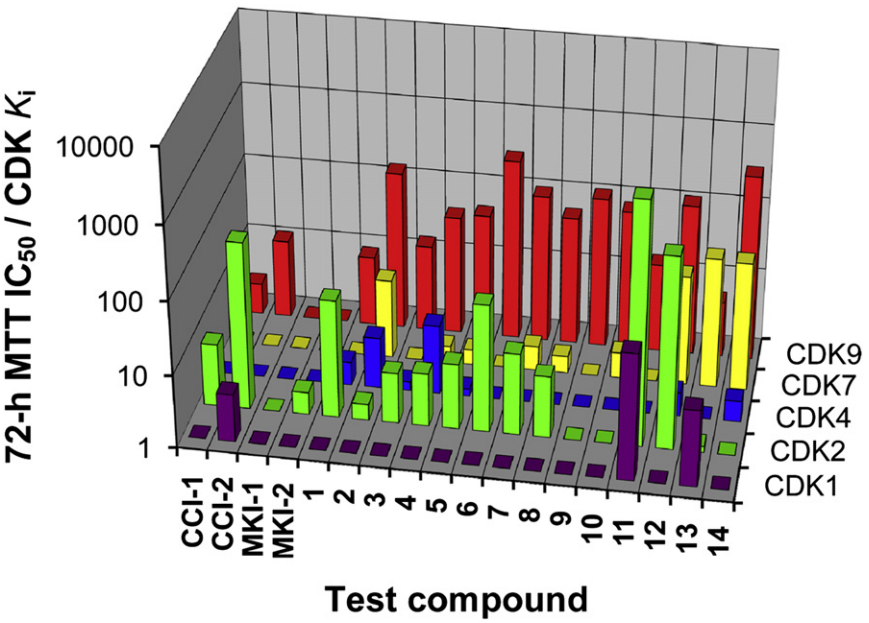



**Figure 2. Cellular CDK Selectivity**

For each test compound the antiproliferative 72 hr MTT assay $IC_{50}$ value against A2780 cells was divided by the $K_i$ values against individual CDKs (determined in biochemical kinase assays) and the ratios were plotted. A low ratio (ratios of $\leq 1$ are shown as unity for the sake of clarity) indicates that antiproliferative activity is unlikely to be due to inhibition of the CDK in question. It is apparent that CDK9 inhibition is important for all transcriptional inhibitors (**1**–**10** and **14**). No other kinase tested shows such a correlation. Of the nontranscriptional inhibitors, **11**, **12**, and **CCI-2** show potentially significant cellular inhibition of CDK9 but these compounds also show strong activity against other kinases. See also Figures S2.

(Figure 3B). This was observed in all tumor cell lines tested where an intact caspase-3/7 pathway was present, irrespective of mutant or wild-type p53 status. Class-1 compounds thus lead to apoptotic tumor cell death, and not to a stage-specific cell cycle block.

## CDK Transcriptional Inhibitor Analogs: Design and Lead Optimization

The 2-anilinopyrimidine compounds in Table 1 were prepared using procedures as described (Wang et al., 2004a). Previously established SARs of a series of 2-anilino-4-(thiazol-5-yl)pyrimidines with respect to CDK2 suggested the importance of substituents at *C*2 of the thiazole ring (Wang et al., 2004a). Introduction of amino functions in the context of either *meta*- or *para*-substituted anilines at the pyrimidine *C*2 resulted in increased inhibition not only of CDK2, but also CDK9. CDK2-bound crystal structures of such compounds, e.g., **1**, reveal that the thiazole *C*2-amino group interacts strongly with the $Asp^{145}$ and $Lys^{33}$ side chains and enhances the hydrophobic interaction of the thiazol-4-yl methyl group with the Phe gatekeeper residue present in all CDKs ($Phe^{80}$ in CDK2) (Wang et al., 2004a). In addition, a number of H-bonding interactions between the thiazole *C*2-alkylamino groups and $Gln^{131}$ and $Asp^{86}$ were also observed. Substitution of the thiazole *C*2 with bulkier groups, such as phenyl, pyridyl, or other heterocycles, resulted in significantly reduced activity. The thiazol-4-yl methyl group was also found to be intolerant of modification. Certain *meta*- or *para*-substitutions of the aniline ring were well tolerated and manipulation of these substituents led to a number of inhibitors possessing varying CDK selectivity profiles. Similar substituents in the *ortho* position abolished CDK-inhibitory activity in all cases.

Application of our screening cascade revealed that compounds with the transcriptional inhibitor phenotype predominantly inhibit CDK7 and CDK9 and show varying selectivity toward other CDKs, in particular CDK2 and CDK4, in enzymatic assays (Figure 2). A derivative with a sulfonamide substituent at the aniline *meta* position and containing a methylamino group at the thiazole *C*2 position (**3**) was found to be one of the most potent transcriptional inhibitors in the class (Table 1). This compound also showed considerable potency against CDK2-cyclin E and CDK4-cyclin D1. Furthermore, it exhibited potent in vitro antitumor activity in a number of cancer cell lines. Replacement of the methylamino with an ethylamino group at thiazole *C*2 afforded another comparatively selective inhibitor of CDK7 and CDK9 (**2**), although with reduced potency. This also resulted in a substantial reduction in antiproliferative activity against tumor cell lines.

Methylation of the sulfonamide at the *meta* position of the aniline ring (**4**) also reduced CDKs 9, 2, and 4 activity somewhat compared to compound **3**. Again this was accompanied by an antiproliferative potency reduction. Analog **5**, which has a primary amino group at the thiazole *C*2 showed potency and selectivity profiles comparable to **4**. Similar antiproliferative activity was observed for both compounds. Replacement of the sulfonamide of **3** with a methylsulfonyl function afforded another picomolar CDK9 inhibitor (**6**) that retained similar potency and selectivity with respect to CDKs 1, 2, and compared to **3**. The structural modification resulted in 10-fold lower activity against CDK4, however. As expected, **6** also displayed potent cytotoxicity in cells. Keeping the aniline portion of **6** constant, but replacing the thiazole *C*2 substituent with the larger ethylamino group led to **7**, with 5-fold reduced inhibition of CDK2 and 3-fold reduced inhibition of CDK9 compared with **6**. An ethyl group on the sulfonamide function (**8**), rather than the methylsulfonamide in **5**, in the context of the thiazole *C*2 primary amine, resulted in slightly reduced potency throughout.

In order to assess if targeting CDK9 alone would be sufficient for a compound to exhibit the transcriptional inhibitor phenotype, a number of selective CDK9 inhibitors were designed. During lead optimization, we observed that introduction of bulky substituents at the *meta* position of the aniline resulted in unfavorable contacts with CDK1 and CDK2, whereas simple nonionizable alkyl functions at the *para* position were poorly tolerated in terms of CDK4 activity. Combination of such substitution

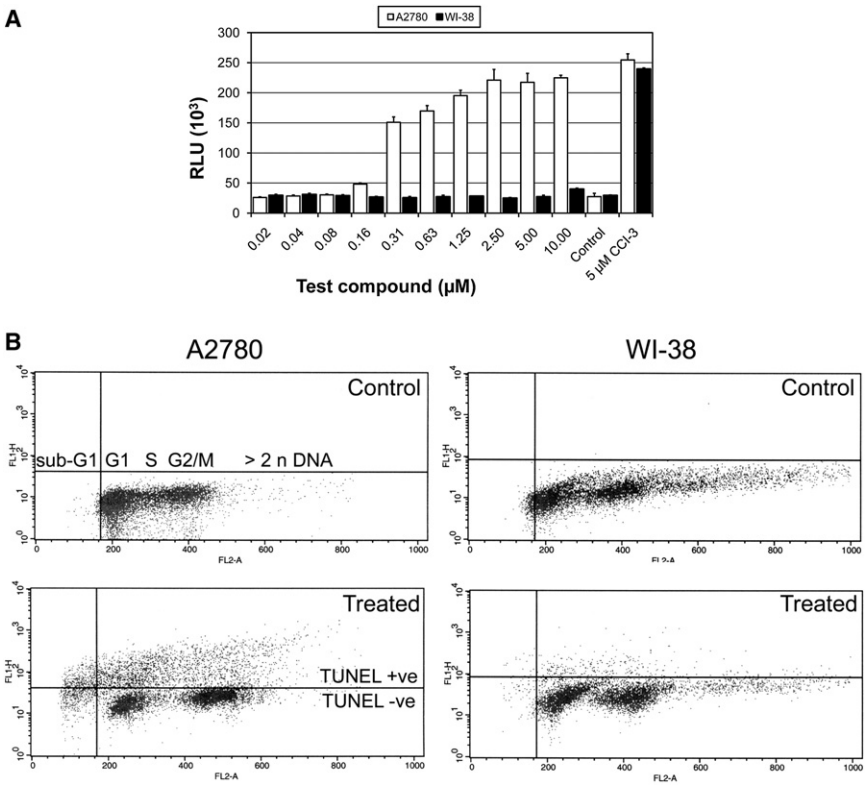



**Figure 3. Selective Induction of Apoptosis in Transformed Cells**

(A) Caspase-3/7 activation assays show **14** selectively to induce caspase activation in the transformed A2780 cell line but not in the non-transformed WI-38 line. Treatment with CCI-3 demonstrates caspase induction in both cell lines. (B) Flow cytometric analysis was performed and cell death (by TUNEL assay gating; ordinate) was correlated with cell cycle stage (by DNA content gating; abscissa). Cells were treated with assay diluent only (control) or with 2 μM compound **14** (treated) for 24 hr. Treatment with **14** (2 μM) resulted in 31% TUNEL-positive A2780 cells corresponding to all cell cycle phases, whereas similar treatment of WI-38 cells gave rise to only 4.8% TUNEL-positive cells. See also Table S2. Data are represented as mean ± SD.

patterns in individual compounds led to the 4-methyl-3-(morpholine-4-sulfonyl)aniline derivatives **9** and **10**. Both compounds were potent CDK9 inhibitors essentially devoid of activity against CDKs 1, 2, and 4, while retaining modest potency against CDK7. Application of **9** and **10** in the screening cascade revealed that both compounds clearly belonged to class-1. However, these compounds exhibited reduced cellular potency in comparison to other low nanomolar $K_i$ CDK9 inhibitors, which, in contrast, were potent against one or more additional CDKs.

Structural modification by transposition of various sulfonamide or alkylsulfone functions from the *meta* to the *para* position of the aniline ring generally resulted in somewhat reduced potency against all CDKs except CDK2. Thus, compound **11**, although active against CDK9, inhibits CDK2 with almost 100-fold higher potency. However, having achieved optimal CDK9 selectivity over CDK2 and CDK4 with compounds such as **9** and **10**, we turned our attention to CDK7 inhibition. We discovered that a number of compounds with a 3*H*-thiazol-2-one (formula **II** in Table 1) rather than a thiazole (formula **I**) system at the pyrimidine *C*4 displayed enhanced potency against CDK7. This was especially true for analogs with a methylated thiazolone *N*3 and small electron-withdrawing aniline *meta* substituents, such as **12**. Addition of a methyl group at the aniline *para* position again improved selectivity and also afforded our most potent CDK7 inhibitor compound **13**.

As noted above, bulky aniline *para* substituents were not conducive to CDK9 selectivity. If, however, substituents containing an amino group that is charged at physiological pH were introduced at the *para* position in the context of the pyrimidinyl *C*4 thiazolone system, both CDK7 and CDK9 potency was preserved, while maintaining selectivity with respect to the other CDKs to some extent. The representative compound in this regard is **14**, which potently inhibits not only CDK7, but also CDK 9. CDKs 1, 2, 4, on the other hand, are inhibited at least 30-fold less potently.

Compound **14** was also assessed for its selectivity in a panel of closely related non-CDK kinases. The results in Table S1A show that a range of kinases are inhibited by **14** at the mid-nanomolar to low micromolar $IC_{50}$ level. Considering the fact that **14** is a mid-picomolar $IC_{50}$ CDK9 inhibitor and comparing with the non-CDK kinase inhibited most potently (VEGFR2 $IC_{50}$ = 180 nM), this gives a selectivity of at least 400-fold. This compound was also passed through a more extensive protein kinase panel that contains kinases representing most signaling pathways. The results again show that certain non-CDK kinases are inhibited by **14**, but at concentrations several orders of magnitude higher than those relevant to CDK7 and CDK9 inhibition (Figure S1C).

Compound **14** was further assessed for its biopharmaceutical properties (Table S1B): it has low lipophilicity (logP = 1.1) and good aqueous solubility. Membrane permeability was moderate with a $P_{app}$ value of $2.4 \times 10^{-6}$ cm/s by Caco-2 monolayer assay. Furthermore, **14** exhibited good in vitro metabolic stability with a half-life of 50 min and low intrinsic clearance in a liver microsome assay. Plasma protein binding was also low (36% unbound fraction). In order to confirm this, **14** was subjected to rat pharmacokinetic (PK) analysis following a single intravenous (i.v.) dose of 5 mg/kg or an oral (p.o.) dose of 50 mg/kg. Mean plasma concentrations were used to calculate the PK parameters (Table S1B). The compound was found to be orally bioavailable (F = 70%) with a plasma half-life of ~5 hr following p.o. administration, and a large volume of distribution. The exposure values obtained show that multiples of in vitro bioactive concentrations can easily be achieved at good dose potency.

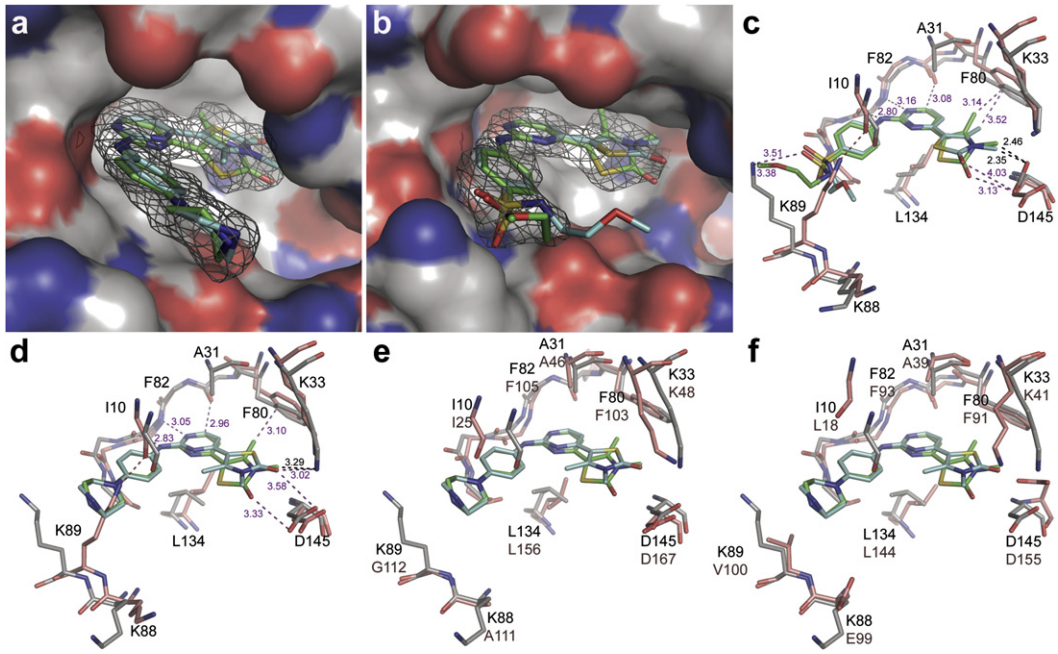



**Figure 4. Structural Basis for Compound CDK Selectivity**

Electron density (gray mesh) and two plausible binding conformations (green and cyan CPK sticks) each for **14** (A) and **11** (B) (contoured at 1.2 and 1.0 σ, respectively) in the complex crystal structures with CDK2 (gray CPK surface). Observed interactions of **11** (C) and **14** (D) with the ATP-binding site of CDK2 (gray), corresponding residues from an aligned structure of a catalytically competent CDK2-cyclin A-ATP/Mg structure are shown (PDB #1QMZ; salmon). Broken lines indicate energetically favorable (magenta) and unfavorable (black) interactions (distances are indicated in Å). Superimposition of the CDK2-**14** complex (gray) with a CDK9 (PDB #3BLR; salmon; E) and a CDK7 crystal structure (PDB #1UA2; salmon; F). The rmsd for the alignment of the CDK9 and CDK7 with the CDK2-**14** coordinates (all atoms/ATP-binding site) was 2.39 Å/0.78 Å and 1.65 Å/0.92 Å, respectively. For data collection and refinement statistics of the X-ray crystal structure complexes of CDK2 with compounds **11** and **14** refer to Table S3; PDB #2XMY and 2XNB.

## Structural Rationale for Potency and Selectivity of Transcriptional Inhibitors

In order to determine the basis for the selectivity and potency of CDK7 and CDK9 inhibitors, we determined complex crystal structures with CDK2 for compounds **11** and **14** (Figures 4A–4D). Furthermore, we used published X-ray crystal structures of CDK7 (Lolli et al., 2004) and CDK9 (Baumli et al., 2008).

The CDK7 and CDK9 selectivity of compound **14**, which contains a piperazine substituent at the aniline *para* position, can be rationalised by the replacement of $Lys^{89}$ in CDK2 with smaller residues in CDK7 and CDK9 (Figures 4E and 4F). Our CDK2-**14** complex crystal structure reveals that the bulky piperazine ring results in unfavorable contacts with the $Lys^{89}$ side chain (Figure 4D). As a result, this side chain is forced to change position from that observed in apo- and ATP-bound CDK2 structures (Brown et al., 1999; Wu et al., 2003), which is energetically unfavorable. On the other hand, modeling suggests that the residues corresponding to $Lys^{89}$ in CDK2, *i.e.* $Val^{100}$ in CDK7 or $Gly^{112}$ in CDK9 can better accommodate the piperazine ring of **14**. The complex structure of compound **14** with CDK2 and homology modeling with other CDKs further indicate that electrostatic charge differences at the ATP-binding site of CDK1 and CDK2 with respect to CDKs 4, 7, and 9 play a significant role in the selectivity of this compound. Because CDKs 4, 7, and 9 all have a nonionizable side chain in the $Lys^{89}$ position, there is less repulsion with the positive charge on the piperazine ring (McInnes et al., 2004).

For compound **11**, which, unlike the piperazine ring of compound **14**, has a flexible sulfonamide substituent, the situation is different. Here the *p*-anilino sulfonamide can be observed to make strong H-bonding interactions with the side-chain amino group of $Lys^{89}$ in CDK2 (Figure 4C). Similar interactions are not possible with CDK7 and CDK9, where small lipophilic residues are present in place of $Lys^{89}$.

The selectivity of the methylsulfone compounds **6** and **7** derives from differences in the residues that correspond to $Gln^{131}$ in CDK2. This is $Ala^{153}$ in CDK9, which is capable of forming favorable van der Waals contacts with the sulfone methyl groups. The increasing CDK9 selectivity of compounds **4**, **5**, and **8–10**, on the other hand, can be explained by the increase in steric bulk of the extensions of the sulfonamides at the aniline *meta* position. As we have shown, compounds with small aniline *meta* substituents, e.g., the nitro derivative **1**, adopt CDK2 binding poses with two distinct aniline orientations (Wang et al., 2004a). Modeling shows that unfavorable intramolecular interactions of the sulfonamide extensions in compounds **4**, **5**, and **8–10** with the thiazole/thiazolone head groups force the aniline rings to project toward the position occupied by $Lys^{89}$ in CDK2, resulting in unfavorable contacts. From the crystal structures of CDK7 and CDK9 it is apparent that the region around $Lys^{88}$-$Lys^{89}$ (in the CDK2 context) is considerably more open in CDK7, and especially in CDK9, due to the presence of the smaller side chains of the corresponding residues ($Glu^{99}$-$Val^{100}$ and $Ala^{111}$-$Gly^{112}$ in CDK7 and CDK9, respectively).

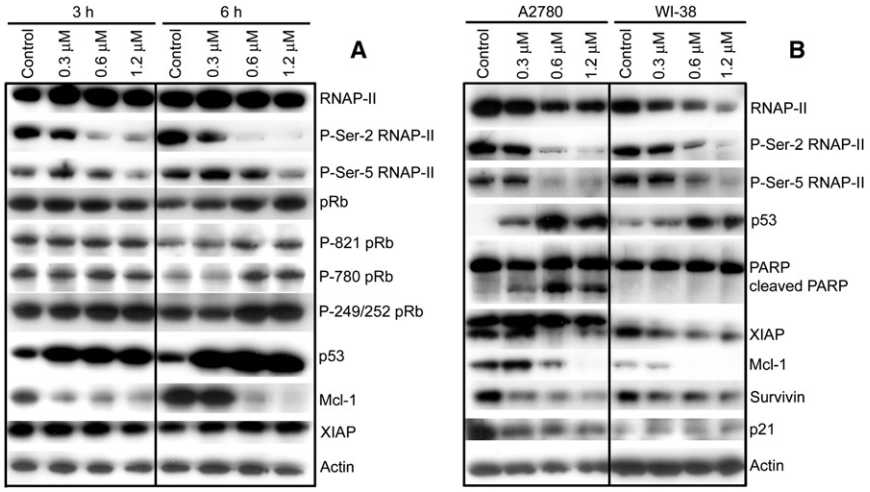



**Figure 5. Status of Key Cellular Proteins Following Treatment with Compound 14**

After exposure of A2780 cells to **14** (A) CTD phosphorylation of Ser-2 and Ser-5 of RNAP-II is significantly reduced after 3 hr. p53 levels have increased and levels of the antiapoptotic protein Mcl-1 have been reduced, while XIAP remains fairly constant at early time points. There is no reduction in phosphorylation of pRb at the 249/252, 780, or 821 sites. After 24 hr treatment with **14** (B) both the transformed A2780 and untransformed WI-38 cell lines show a similar primary response. There is a reduction in phosphorylation of the CTD of RNAP-II at Ser-2 and Ser-5, an increase in p53, and a decrease in each of the antiapoptotic proteins XIAP, Mcl-1, and survivin. Only A2780 cells show cleavage of PARP, however, suggesting that apoptosis has been initiated in these cells. See also Figure S3.

## Cellular Mode of Action of Compound 14

### *In Vitro Antiproliferative Activity*

On the basis of its in vitro kinase potency, selectivity, and pharmaceutical properties, a detailed study of the cellular mode of action of **14** was carried out. It was screened against a panel of human leukemia and solid tumor cell lines (Table S1C). A broad spectrum of in vitro antitumor activity was observed, with an average $IC_{50}$ value of 0.3 μM. There was no selectivity toward cell line types based on p53, p21, p16, or pRb status. Selectivity toward transformed versus untransformed cell lines was observed: **14** was 20- and 40-fold less potent against fetal lung fibroblast lines WI-38 and IMR-90, respectively, compared with the tumor cell lines examined.

### *RNAP-II CTD Phosphorylation and p53 Induction*

In accordance with the biochemical enzyme inhibition data showing **14** to be a potent inhibitor of CDK7 and CDK9, the phosphorylation of both Ser-2 and Ser-5 of the RNAP-II CTD was reduced significantly after 3 hr in A2780, with WI-38 cells showing a similar response at 24 hr (Figure 5). Protein levels of p53 were induced at early time points since p53 is regulated at the translational level, but p21 levels, normally upregulated by p53-dependent transcription, did not rise due to inhibition of transcription by **14**.

### *Reduction of Antiapoptotic Protein Levels*

At 3 hr, Mcl-1 levels were reduced in A2780 cells. After 24 hr, A2780 and WI-38 cells both showed a reduction in antiapoptotic proteins XIAP, Mcl-1, and survivin (Figure 5). A2780 cells showed a greater reduction in levels of survivin and XIAP than WI-38 cells. Both cell lines showed reductions in Mcl-1. It is interesting to note that A2780 cells possess much greater levels of Mcl-1 than WI-38 in untreated samples.

### *Selective Induction of Apoptosis in Transformed Cells*

Apoptosis is induced in A2780 cells, as detected by caspase-3/7 assay, at concentrations of 0.31 μM **14** and above. WI-38 cells, however, were completely insensitive even at 10 μM **14** (Figure 3A), despite showing sensitivity to mechanistically unrelated kinase inhibitor compounds. This result confirms the selectivity for transformed cells seen in the MTT proliferation assay (Table S1C). TUNEL analysis, in conjunction with DNA staining, showed that 50% of cells were TUNEL positive after 24 hr with 2 μM **14** (Figure 3B). These apoptotic cells were observed in all cell cycle compartments, suggesting that this class of inhibitor causes cell death at each stage of the cell cycle and does not lead to a stage-specific cell cycle block. A reduction in the levels of antiapoptotic proteins occurred in both transformed (A2780) and untransformed (WI-38) cell lines. However, PARP cleavage (Figure 5) only occurred in the A2780 cell line, suggesting that antiapoptotic proteins may play a less important role in the untransformed cells than in the oncogenically transformed cells.

### *Selective CDK9-Cyclin T Inhibition Also Induces the Transcriptional-Type Response in Cells*

Compounds **3**, **10**, and in particular, compound **9**, showed greater selectivity for CDK9 over CDK7. Figure 2 shows that at the concentrations of compounds needed to induce cellular cytotoxicity, the contribution of CDK7 inhibition is negligible. From the screening cascade these compounds belonged to class-1 and further analysis of key cellular proteins showed a significant reduction in RNAP-II CTD Ser-2 phosphorylation, a slightly weaker reduction in Ser-5 phosphorylation, an induction of p53, and a reduction in Mcl-1 levels after 3 hr exposure in A2780 cells (Figure S3). These responses are consistent with that shown by **14**, an approximately equipotent CDK7 and CDK9 inhibitor. Like **14**, the CDK9-specific inhibitors **3**, **9**, and **10** induced apoptosis selectively in transformed cells (Table S2).

## In Vivo Anti-Tumor Activity of Compound 14

Compound **14** was evaluated for in vivo antitumor activity using a P388/0 murine leukemia survival model (Marsh et al., 1985). When dosed twice daily for 10 days with **14**, animals experienced an increase in life span of 68%, 45%, and 36% at doses of 30, 20, and 13 mg/kg/dose, respectively ($p < 0.0001$) (Figure S2A). The treated animals suffered no weight loss compared to animals receiving vehicle only and the maximum tolerated dose (MTD) of **14** was not achieved in this experiment, indicating a good therapeutic margin.

Compound **14** also demonstrated antitumor activity in a murine xenograft solid tumor model using the human colorectal Colo-205 cell line. As a positive control 5-fluorouracil (5-FU), the chemotherapy drug most commonly used in the clinic for colorectal cancer, was included on an optimal intravenous

dosing regimen at the MTD. The test compound **14** was administered by either the intraperitoneal (i.p.) or oral route (Figure S2B). When given at 50 mg/kg i.p. every day for 8 days, **14** produced a specific tumor growth delay of 10.5 days ($p < 0.05$). Similarly, **14** was active and well tolerated when given by the same schedule at 100 mg/kg p.o., resulting in a tumor growth delay of 7 days ($p < 0.05$). On the last evaluable day the tumor versus control ratios (T/C) were below 40% at the top dose by both administration routes. By comparison, 5-FU was considerably less active at its MTD of 50 mg/kg, given every 4 days for four treatments, and only yielded a tumor growth delay of 1 day.

## DISCUSSION

The work presented here explores the biomedical rationale for the development of pharmacological inhibitors of transcription. This effect is achieved with kinase inhibitors that target predominantly CDK9-cyclin T1 and is further explored by studying the effects of simultaneously inhibiting CDK7 and CDK2, additional CDKs thought to be responsible for the regulation of RNAP-II activity through phosphorylation of its CTD.

The current model of RNAP-II regulation postulates a sequence in which CDK7 first phosphorylates CTD Ser-5 residues as part of transcription initiation (Sims et al., 2004). Subsequent dephosphorylation of Ser-2, and then phosphorylation of Ser-2 residues by CDK9 (Zhou et al., 2000) is necessary for the transition to RNA elongation (Price, 2000). Detailed analysis of CTD phosphorylation by CDKs 7, 8, and 9 (Ramanathan et al., 2001) have shown all three kinases to be capable of phosphorylating Ser-5, but not Ser-2, of a CTD peptide in vitro, despite evidence of in vivo phosphorylation at both Ser-2 and Ser-5 residues. This seems to correlate with the concept of stepwise phosphorylation, with Ser-5 phosphorylation being the initiating event, while Ser-2 becomes phosphorylated only after other criteria are met. Another study has highlighted the nonuniformity of CTD phosphorylation, showing that each of the three kinases produces different patterns of phosphorylation of the CTD, but that only CDK7 efficiently produces hyperphosphorylated substrates (Pinhero et al., 2004). These studies suggest that CTD phosphorylation is regulated in a complex manner, with changes in substrate specificity depending upon the transcriptional state of the complex and the accessibility of different regions of the CTD.

Each of our transcriptional-type inhibitor compounds is capable of reducing the phosphorylation of Ser-2 and Ser-5 of the CTD of RNAP-II. There is a differential response in the phosphorylation state of Ser-2 and Ser-5, with quicker and more pronounced dephosphorylation of Ser-2 over Ser-5. At this stage we cannot conclusively demonstrate kinase specificity for each site as this difference may be due to different phosphatase activities or site accessibility. However, compounds **3**, **9**, and **10**, that we postulate to possess no appreciable CDK7 activity at the concentrations used to elicit a cytotoxic $IC_{50}$ response (Figure 2), can still cause a reduction in Ser-2 phosphorylation after 3 hr and initiate events that lead to the subsequent induction of apoptosis. These data lend support to the hypothesis of CDK9 targeting the Ser-2 site of RNAP-II and that inhibition of CDK9 is sufficient to inhibit transcription.

The transcriptional activity of RNAP-II is required in all cells and inhibition of RNAP-II may thus not immediately present itself as a rational target for cancer therapeutics. However, transformed cells have a greater requirement for enhanced transcriptional activity. First, their increased rate of proliferation necessitates increased protein production. Second, cells are genetically predisposed to enter into programmed cell death upon oncogenic stimulation, but a few may be able to transform into an apoptosis-resistant, rapidly proliferating state by a number of means. One way of avoiding apoptotic death is the increased production of antiapoptotic proteins in order to counteract the presence of the proapoptotic proteins induced by the initial transforming event (Koumenis and Giaccia, 1997). The cancer cell achieves a new balance, but at the expense of continuously increased production of these antiapoptotic proteins, many of which have short half-lives at both the mRNA and protein levels. The fully transformed cell is thus committed to a strategy of increased protein production and therefore increased transcription in order to maintain the status quo of cell survival over programmed cell death.

The increased production of antiapoptotic proteins in transformed cells is well documented (Liston et al., 2003; Schimmer, 2004). For example, elevated levels of survivin, XIAP, cIAP1, and cIAP2 have been shown in human prostate cancers and in prostate tissues from transgenic mice expressing SV40 large T antigen (Krajewska et al., 2003). Survivin is highly expressed in many transformed cells but is rarely detected in normal adult tissues (Zangemeister-Wittke and Simon, 2004). Mcl-1 is a member of the anti-apoptotic Bcl-2 family (Cory et al., 2003) whose expression decreases when cells undergo apoptosis (Iglesias-Serret et al., 2003). Increased Mcl-1 protein levels have been reported in a number of tumor samples (Khoury et al., 2003; Song et al., 2005), and a difference in expression may be observed in the control lanes of A2780 and WI-38 (Figure 5).

We show that as a result of decreased transcription, the expression levels of a number of highly expressed, short half-life, antiapoptotic proteins such as Mcl-1, survivin, and XIAP decline rapidly in both transformed and untransformed cell lines. We demonstrate that although the primary events of dephosphorylation of RNAP-II, induction of p53, and downregulation of antiapoptotic proteins, is consistent across transformed and untransformed lines, the ultimate fate of the cell is governed by its reliance upon antiapoptotic proteins for continued survival. This results in a selective apoptotic response, demonstrated by strong induction of caspase-3/7 activity, PARP cleavage, and appearance of TUNEL-positive cells in transformed cell lines only.

The induction of p53, a protein whose expression is tightly regulated at the posttranslational level by its association with Mdm2, itself a short half-life protein that is affected by reduced transcriptional activity, may contribute to the apoptotic response. p53 may translocate to the mitochondria and induce apoptosis through its direct interaction with, and activation of proapoptotic proteins such as Bax (Arima et al., 2005). However, as we see no differential sensitivity between p53 wild-type and p53 mutant or null cells in our cytotoxicity assays and have demonstrated that the response is not part of a DNA damage response, we conclude that this effect is not integral to compound mode of action and we simply utilize this induction as part of our screening cascade. The increase in p53 levels is

not accompanied by increased p21 levels (a protein normally regulated by p53 activity), a response in keeping with transcriptional inhibition.

## SIGNIFICANCE

**The work described here highlights our current understanding of transcriptional-type CDK inhibitors and demonstrates how this knowledge can be adapted to provide an efficient screening cascade for the identification of such compounds. We have profiled a number of compounds with the ability to reduce the phosphorylation of Ser-2 and Ser-5 of the CTD of RNAP-II through inhibition of CDK9-cyclin T and CDK7-cyclin H and selectively kill transformed cells as a result of this inhibition. Our work shows that although both transformed and untransformed cells show a similar reduction in antiapoptotic proteins due to inhibition of RNAP-II CTD phosphorylation, untransformed WI-38 lung fibroblasts do not undergo apoptosis, thus demonstrating a differential response to the downstream events that cause transformed cells to undergo apoptosis through the caspase pathway. In vivo experiments have also demonstrated a good tolerance for compound 14 and significant increases in life span and antitumor activity in mouse models. We thus conclude that an untransformed cell, with intact checkpoints, low oncogenic stress, and lower levels of apoptotic proteins may have a significant tolerance toward transient inhibition of RNAP-II activity, whereas the equivalent transformed cell would be much more susceptible to this type of inhibition and undergo a caspase-induced apoptotic death.**

## EXPERIMENTAL PROCEDURES

### Synthesis and Compound Characterization

Preparation of *[4-(2-amino-4-methyl-thiazol-5-yl)-pyrimidin-2-yl]-(3-nitro-phenyl)-amine* (**1**) was described (Wang et al., 2004a). Compounds **2**–**14** were prepared in the same manner. Details are provided as Supplemental Experimental Procedures.

### Cell-Based Assays

#### *Mitotic Index Assay*

MI was determined by an automated fluorescence microscopy 96-well plate assay using the Cellomics Arrayscan Mitotic Index HitKit protocol (Cellomics Inc.). In brief, cells were plated at $10^4$ cells per well and incubated for 18 hr at 37°C. Test compounds were added and cells were incubated for the appropriate time before a 15 min fixation in 3.7% formaldehyde in PBS. Cells were permeabilized in PBS with 0.2% Triton X-100 for 15 min, washed, and incubated with a primary antibody that specifically recognizes a mitotic epitope (rabbit anti-phosphoserine-10 histone-H3, Upstate 06-570). After incubation with a secondary FITC-conjugated anti-rabbit antibody and Hoechst 33258 dye, cells were washed and analyzed using the Cellomics Arrayscan II automated fluorescent microscopy system to detect nuclear fluorescent staining. Data for 2000 cells per well were collected and the Cellomics mitotic index algorithm used to calculate mitotic index (MI; percentage of cell nuclei stained with the mitosis-specific antibody versus total cell nuclei stained with Hoechst 33258 dye). A similar assay was carried out for DNA damage by substituting a mouse antibody specific for the DNA damage marker histone H2AX (Upstate 17-327A) as the primary antibody and FITC-conjugated anti-mouse antibody as secondary antibody.

#### *p53 Stabilization Assay*

Cells were plated at $10^4$ cells per well and incubated for 18 hr at 37°C. Test compounds were added and cells were incubated for the appropriate time before a 3 min fixation in cold (−20°C) 50:50 v/v methanol/acetone. The fixed cells were dried briefly then washed with PBST (PBS, 0.1% Triton X-100) and incubated with primary CM-1 rabbit anti-human p53 antiserum (Midgley et al., 1992) diluted 1:1,000. After incubation with a secondary Alexa Fluor 488 goat anti-rabbit antibody (Molecular Probes, A11008) and Hoechst dye, the cells were washed and analyzed using the Cellomics Arrayscan II automated fluorescent microscopy system to detect nuclear fluorescent staining. Data for 2000 cells per well were collected and the Cellomics mitotic index algorithm used to calculate percentage of cell nuclei stained with p53-specific antibody versus total cell nuclei stained with Hoechst.

#### *MTT Cytotoxicity Assays*

Standard MTT (thiazolyl blue; 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide) assays were performed after 72 hr treatment with test compounds (Haselsberger et al., 1996).

#### *Determination of Apoptosis*

Apoptosis was determined by either a terminal deoxynucleotidyl transferase-mediated nick end labeling (TUNEL) assay (ApoDirect BD), following manufacturer's instructions, or by caspase-3/7 assay (Caspase-Glo 3/7 assay, Promega), following manufacturer's instructions, with cells seeded at 10,000 per well of a 96-well plate in a total volume of 100 μl medium per well. Assays were performed 24 hr after test compound addition. Detection reagent (100 μl) was added directly to each 100 μl sample and readings were taken after a further 30 min incubation at room temperature.

#### *Western Blot Analysis*

Total protein cell lysates (10 μg) were run on SDS-PAGE (4%–12% gradient) gels (Novex) under reducing conditions. The separated proteins were transferred to membranes and were probed with antibodies specific for pRb (BD), 249/252 pRb (BioSource), RNAP-II, RNAP-II Ser-2, RNAP-II Ser-5 (Covance), p53 (Oncogene ab-6), p21, PARP, Mcl-1 (Santa Cruz), XIAP, survivin (Novus), and actin (Sigma).

### In Vitro Kinase Assays

Details for the cloning, expression, and purification of His-tagged CDK9/cyclin T1 are provided as Supplemental Experimental Procedures.

#### *Kinase Assays*

CDK and other kinase assays were carried out as previously described (Wang et al., 2004a). $IC_{50}$ values were calculated from ten-point dose-response curves and apparent inhibition constants ($K_i$) were calculated from the $IC_{50}$ values and appropriate $K_m$ (ATP) values for the kinases in question (Cheng and Prusoff, 1973).

### Pharmacology

Screening, biopharmaceutical profiling, PK determinations, and evaluation of anti-tumor efficacy of test compounds are described in the Supplemental Experimental Procedures.

## ACCESSION NUMBERS

The coordinates of the X-ray crystal structures of compounds **11** and **14** in complex with CDK2 have been deposited with the PDB (www.rcsb.org) under accession codes 2XMY and 2XNB.

## SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, three figures, and three tables and can be found with this article online at doi:10.1016/j.chembiol.2010.07.016.

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