A series of \(\text{N}-(1\text{-benzyl-1H-1,2,3-triazol-4-yl})\text{methyl}\text{arylamides was synthesized by copper-catalyzed azide–alkyne cycloaddition (CuAAC) and afforded inhibitors of cancer cell growth. For example, compound 13e had an IC}_{50} \text{ of 46 nM against MCF-7 human breast tumor cells. Structure–activity relationship (SAR) studies demonstrated that (i) meta-phenoxy substitution of the 1-benzyl group is important for antiproliferative activity and (ii) a variety of heterocyclic substitutions for the aryl group of the arylamide are tolerated. In silico COMPARE analysis of antiproliferative activity against the NCI-60 human tumor cell line panel revealed a correlation to clinically useful antimicrotubule agents such as paclitaxel and vincristine. This in silico correlation was supported by (i) in vitro inhibition of tubulin polymerization, (ii) G2/M-phase arrest in HeLa cells as assessed by flow cytometry, and (iii) perturbation of normal microtubule activity in HeLa cells as observed by confocal microscopy. The results demonstrate that \(\text{N}-(1\text{-benzyl-1H-1,2,3-triazol-4-yl})\text{methyl}\text{arylamide is a readily accessible small molecule scaffold for compounds that inhibit tubulin polymerization and tumor cell growth.}

Herein we report the synthesis, in vitro antiproliferative activity against select cancer cell lines, and structure–activity relationships of compounds containing the \(\text{N}-(1\text{-benzyl-1H-1,2,3-triazol-4-yl})\text{methyl}\text{arylamide scaffold. We also report mode of action studies based on in silico, in vitro, and cell culture experiments, which reveal the potent antimicrotubule activity of this scaffold. The discovery of this scaffold stemmed from our work on Mycobactin S (1), a natural product produced by \textit{Mycobacterium smegmatis} that exhibits antituberculosis activity (11) (Chart 1). All synthetic intermediates encountered during our group’s total synthesis of Mycobactin S (12) were screened for biological activity. Surprisingly, benzyl ester 2, a small fragment of the natural product, exhibited antituberculosis activity similar to that of Mycobactin S. Furthermore, in contrast to Mycobactin S, compound 2 provided a scaffold that was amenable to rapid structure–activity relationship studies, which led to the discovery of more potent antituberculosis agents. (13) While exploring derivatives of 2, we found that 2-phenyl-oxazole-4-carboxamide derivative 3 was also active against \textit{M. tuberculosis}. 2-Phenyl-oxazole-4-carboxamides are known inhibitors of histone deacetylase. (14) Stat3, (15) phosphodiesterase, (16) phosphatase, (17) thromboxane synthase, (18) kinase proteins, (19) and known activators of cellular caspase activity. (20) We synthesized derivatives of 3 to identify a more potent antituberculosis agent. (13) One of the derivatives, compound 4e, had weak antituberculosis activity, but broader biological screening serendipitously revealed that 4e and related derivatives have potent antimicrotubule activity in cancer cells, as disclosed in this report.

**Introduction**

Microtubules, dynamic protein polymers composed of \(\alpha\)-tubulin and \(\beta\)-tubulin heterodimers, are a well-established cellular target for anticancer drugs. (1) Dynamic polymerization of tubulin is a necessary and tightly controlled process during mitosis. (2) Perturbing microtubule dynamics with small molecules blocks the cell cycle in the metaphase/anaphase transition and leads to apoptosis. (3) Thus, molecules that target tubulin halt rapid cell division, a characteristic of cancer cells. (2) This therapeutic strategy has been validated by the clinical success of antimicrotubule drugs such as paclitaxel, docetaxel, vincristine, and vinblastine. Nonetheless, neurotoxicity and P-glycoprotein-mediated drug resistance limit the clinical utility of these drugs. (6) New-generation taxoids, vinca alkaloids, and other novel chemotypes that modulate microtubule dynamics have been synthesized in efforts to overcome these limitations. (7) For example, small molecule modulators of tubulin polymerization that do not elicit neurotoxicity in mice have been identified, (8) suggesting that neurotoxicity is not intrinsically linked to antimicrotubule agents. Nonetheless, few of these new antimicrotubule agents have produced useful clinical results. The key limitation to the development of new antimicrotubule drugs is a narrow therapeutic window. (9) A new antimicrotubule scaffold amenable to rapid derivatization and combinatorial library synthesis would provide an exceptional opportunity for the discovery of an efficacious antimicrotubule agent with an improved therapeutic window.
Results and Discussion

Chemistry. 2-Phenyl-oxazole-4-carboxylic acid 7 was synthesized according to the protocols shown in Scheme 1.11,12 Coupling benzoyl chloride to serine benzyl ester hydrochloride afforded β-hydroxy amide 5. Dehydrative cyclization and oxidation of β-hydroxy amide 5 with diethylaminosulfur trifluoride (DAST) and DBU/BrCCl3 yielded oxazole 6.22 Catalytic hydrogenolysis of the benzyl ester provided 2-phenyl-oxazole-4-carboxylic acid 7.

Our strategy for exploring the chemical space around the 2-phenyl-oxazole-4-carboxamide fragment employed “click chemistry.”23 More specifically, we selected the Cu(I)-catalyzed azide–alkyne cycloaddition (CuAAC) reaction24 because of its wide scope, high efficiency, and recognized utility for drug discovery.25 Following this strategy, N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)-2-phenyl-oxazole-4-carboxamides 4a–e were synthesized as shown in Scheme 2. Coupling propargylamine to freshly prepared 2-phenyl-oxazole-4-carboxyl chloride (derived from the corresponding carboxylic acid 7) provided alkyne 8. With the terminal alkyne precursor in hand, we turned our attention to the syntheses of azides 10a–e. Benzyl bromides 9a–e were treated with NaN3 to afford benzyl azides 10a–e.26 Exposing terminal alkyne 8 to benzyl azides 10a–e in the presence of catalytic Cu(I) produced 1,4-disubstituted triazoles 4a–e in high regioselectivity. Aqueous CuAAC conditions (H2O/t-BuOH, 2:1) facilitated precipitation of the products, which were isolated with high purity.24

To explore the structure–activity relationships of the aryl amide group, a more general N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)arylamide scaffold was synthesized according to the protocols shown in Scheme 3. The simplicity of reaction Schemes 2 and 3 is anticipated to allow the synthesis of a large library of 1,2,3-triazole-based structures. Moreover, the CuAAC reaction is the convergent synthetic step. Both the arylamide and benzyl groups, attached to opposite sides of the central triazole, are important components of the pharmacophore, as shown by the structure–activity studies described below. The convergence of the synthesis will allow both sides of the scaffold to be systematically varied in future SAR studies.

In Vitro Antiproliferative Activity. The antiproliferative activity of compounds 4a–e against cancer cells was...
discovered during broad biological screening of a series of compounds originally anticipated to have antituberculosis activity. Although compounds 4a–e had negligible antituberculosis activity, they inhibited the proliferation of cancer cells in vitro. Therefore, we determined the antiproliferative activities (IC50 values) of hit compounds 4a–e against the breast tumor-derived cell line MCF-7 (Table 1). Because the IC50 of 4e (0.56 μM) was significantly lower than those of 4a–d (IC50 = 7.3–16 μM), we conserved meta-phenoxy benzyl substitution at triazole N-1 in the second series of analogues (Scheme 3).

The structure–activity relationships of the triazole C-4 substituent were investigated by changing the carboxamide group (Table 2). In this SAR study, antiproliferative activity was investigated with the MCF-7 cell line and human lymphoma cell line U937. Addition of electron withdrawing or electron donating groups to the para-position of the 2-phenyloxazole group (13a–c) had a significant effect on antiproliferative activity, revealing an avenue for future optimization. Before performing an extensive SAR study via substitution of the 2-phenyloxazole group, we wanted to know if the 2-phenyloxazole was necessary for antiproliferative activity. If simpler aryl groups could replace the 2-phenyloxazole, the three-step synthesis of the 2-phenyloxazole-4-carboxylic acids could be bypassed by using commercial aryl acids. Thus, we conducted a systematic truncation of the 2-phenyloxazole-4-carboxamide group found in 4e. Removing the 2-phenyl group (13d) did not significantly change the activity. Following this lead, which suggested that we could use simpler aryl groups, we synthesized 2-pyridyl derivative 13e. Against the MCF-7 cell line, the IC50 of 13e (46 nM) was significantly lower than that of 4e (560 nM). Likewise, a significant decrease in IC50 was observed with the U937 cell line. Therefore, replacing the 2-phenyloxazole group with simpler aryl groups represents a significant opportunity to improve antiproliferative activity. Phenyl derivative 13f had improved antiproliferative activity compared to 4e but was less active than 2-pyridyl derivative 13e.

Table 1. In Vitro Antiproliferative Activity of Compounds 4a–e, Colchicine, and 2-Methoxyestradiol against Human Breast Cancer Cell Line MCF-7

<table>
<thead>
<tr>
<th>compd</th>
<th>R1</th>
<th>IC50 (μM) MCF-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a</td>
<td>H</td>
<td>15.9</td>
</tr>
<tr>
<td>4b</td>
<td>p-CH3</td>
<td>7.59</td>
</tr>
<tr>
<td>4c</td>
<td>p-CF3</td>
<td>7.33</td>
</tr>
<tr>
<td>4d</td>
<td>m-OCH3</td>
<td>8.35</td>
</tr>
<tr>
<td>4e</td>
<td>m-OPh</td>
<td>0.56</td>
</tr>
<tr>
<td>colchicine</td>
<td></td>
<td>0.013</td>
</tr>
<tr>
<td>2-methoxyestradiol</td>
<td></td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 2. Antiproliferative Activities (IC50) of Compounds 4e, 13a–f, 14, Colchicine, and 2-Methoxyestradiol against Human Breast Cancer Cell Line MCF-7 and Human Lymphoma Cell Line U937

<table>
<thead>
<tr>
<th>Compound</th>
<th>R2</th>
<th>IC50 (μM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e</td>
<td></td>
<td>0.56 ± 0.11</td>
</tr>
<tr>
<td>13a</td>
<td></td>
<td>0.33 ± 0.05</td>
</tr>
<tr>
<td>13b</td>
<td></td>
<td>1.9 ± 1.4</td>
</tr>
<tr>
<td>13e</td>
<td></td>
<td>0.66 ± 0.31</td>
</tr>
<tr>
<td>13f</td>
<td></td>
<td>0.245 ± 0.007</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>0.64 ± 0.35</td>
</tr>
<tr>
<td>Colchicine</td>
<td></td>
<td>0.0134</td>
</tr>
<tr>
<td>2-methoxyestradiol</td>
<td></td>
<td>0.842 ± 0.090</td>
</tr>
</tbody>
</table>

*IC50 values represent the concentration at which the cell count was inhibited to 50% of that measured in the vehicle control. Error is SEM, n ≥ 3.*
Replacing the aryl group with a methyl group (14) gave a meaningful loss of antiproliferative activity and demonstrated the importance of the aryl carboxamide group.

**Time Dependence of In Vitro Cellular Antiproliferative Activity.** To distinguish cytotoxic activity from cytostatic activity, the time dependence of the effect of 13e on MCF-7 cells was determined (Figure 1). At a concentration of 39 nM, 13e slowed the cell proliferation rate. At higher concentrations (78 nM and 156 nM), cellular proliferation was halted, but 13e did not decrease the number of cells. Thus, at concentrations moderately higher than the IC50, 13e is cytostatic rather than cytotoxic against MCF-7 cells.

**Broad-Spectrum In Vitro Antiproliferative Activity.** The NCI-60 anticancer drug screen is an in vitro assay consisting of 60 different human tumor cell lines.27 Organized by disease type, the NCI-60 panel includes various leukemia cell lines and cell lines derived from solid tumor sources. Cell line selectivity guides further biological evaluation. In the NCI-60 panel, compounds 4b, 4c, 4d, and 4e induced broad-spectrum antiproliferative activity against tumor cell lines derived from leukemia, nonsmall cell lung cancer, colon cancer, CNS cancer, melanoma, ovarian cancer, renal cancer, prostate cancer, and breast cancer (see Supporting Information). Of these four compounds, 4c (NCI-60 mean GI50 = 870 nM) was more than 20 times more potent than the other three compounds (Table 3). This result is consistent with the results from our MCF-7 and U937 assays and further emphasizes the importance of meta-phenoxy benzyl substitution of triazole N-1 for optimal activity within this scaffold. With respect to selectivity among the 60 cell lines in the NCI-60 panel, all four compounds tested in the panel showed greater than average potency against human leukemia cell line HL-60, breast cancer cell line MCF-7, and melanoma28 cell line MDA-MB-435 (Table 3).

**COMPARE Analysis Revealed a Correlation to Antimicrotubule Drugs.** For a given compound, the antiproliferative activity measured in the NCI-60 differs by cell line. Furthermore, antitumor agents with similar mechanisms of action can produce similar patterns of differential antiproliferative data. We used the matrix COMPARE algorithm29 to measure the correlations between compounds 4b, 4c, 4d, and 4e with respect to differential antiproliferative activity. The matrix produced by the analysis showed that 4c and 4d have highly correlated activities (r = 0.968) (Table 4). On the contrary, 4e (the most potent compound tested in the NCI-60) had low correlations (r < 0.5) with the other three compounds. These matrix COMPARE results suggest that 4c and 4d have the same mechanism of action, but the mechanism of 4e is distinct. Future studies will further investigate the importance of the meta-phenoxy substituent found in 4e for its mechanism action. In the studies reported here, we focused on 4e and related analogues, which also have the meta-phenoxy substituent, because of their superior potency.

The COMPARE algorithm can also compare the differential antiproliferative activity of a new compound to those of compounds with known mechanisms of action in the NCI Standard Agent Database.31 Standard COMPARE analysis has been used previously to identify the cellular targets of antitumor agents.32 Thus, the pattern of differential antiproliferative activity of 4e was used to probe the NCI Standard Agent Database for correlations. We used all three measures of activity provided by the NCI-60 screen (GI50, TGI, and LC50). Correlation values (r) are Pearson’s correlation coefficients. Some hits appear multiple times because they were tested by the NCI for the Standard Agent Database.31 Standard COMPARE analysis produces similar patterns of differential antiproliferative data. We used all three measures of activity provided by the NCI-60 screen (GI50, TGI, and LC50). Correlation values (r) are Pearson’s correlation coefficients. Some hits appear multiple times because they were tested by the NCI for the Standard Agent Database.31 Standard COMPARE analysis produces similar patterns of differential antiproliferative data.
microtubule polymerization. Given this in silico result, we hypothesized that 4e targets microtubules and directly tested this hypothesis in vitro. In contrast, the first-ranked COM-PARE hits for 4b–d did not include antimicrotubule agents (see Supporting Information).

**Inhibition of Tubulin Polymerization In Vitro.** The polymerization of microtubules from purified tubulin can be monitored in vitro by measuring an increase in light scattering. In this in vitro experiment removes complicating factors, such as microtubule-associated proteins (MAPs), which might be part of a putative target that leads to disruption of microtubules as observed with microscopy. To test our hypothesis that the target of the N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)arylamide scaffold is tubulin, and not a MAP, we monitored the polymerization of tubulin after treatment with 4e, 13a, and 13e (Figure 2). In this experiment, paclitaxel, a microtubule stabilizer, enhanced the rate of tubulin polymerization, while nocodazole, a microtubule destabilizer, prevented the polymerization of tubulin. Similar to nocodazole, 4e, 13a, and 13e completely inhibited tubulin polymerization at 10 μM. Thus, the triazole-based compounds prevent the formation of microtubules in vitro. We followed this in vitro assay with cell culture experiments to see if microtubules are the primary cellular target.

**Cell Cycle Analysis Demonstrated G2/M-Phase Arrest.** Antimicrotubule agents induce M-phase arrest. Flow cytometry can quantitatively determine the population of cells in each phase of the cell cycle by measuring the DNA content of individual cells. Cells in G2-phase or M-phase have twice as much DNA as cells in G1-phase. Thus, we conducted flow cytometric cell cycle analysis of HeLa cells treated with 4e, 13a, 13d, 13e, and 14. Consistent with the hypothesized mechanism of action, compounds 4e, 13a, 13d, and 13e significantly increased the population of cells in G2/M-phase (Figure 3). Upon treatment with these four compounds, the population of G2/M-phase cells increased from 13% in the control to over 90%. Compound 14, however, did not induce significant G2/M-phase arrest, which suggested that the arylamide moiety is important for the antimitotic activity of the N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)arylamide scaffold.

**Confocal Microscopy Showed M-phase Arrest and Disruption of Microtubules.** Visual evidence for M-phase arrest can be seen in Figure 4, which shows confocal microscopy images of HeLa cells after 18 h incubation in the presence of 5 μM compound. Nocodazole is a known tubulin polymerization inhibitor. Nuclear DNA was stained with propidium iodide (red channel), and tubulin was stained with FITC-conjugated anti-α-tubulin antibody (green channel). Compounds 4e and 13e disrupted normal microtubule structures, caused fragmentation of mitotic spindles, and induced M-phase arrest.
be obtained with confocal microscopy due to DNA condensation, resulting in enhanced staining by propidium iodide. This outcome is in contrast to the diffuse staining of DNA in interphase cells. Visual evidence for the disruption of microtubules can be obtained concurrently using a fluorescein isothiocyanate-conjugated antitubulin antibody. We therefore used confocal microscopy to examine HeLa cancer cells treated with compounds 4e and 13e. Both DNA condensation and disruption of microtubules were observed at 5 μM of 4e or 13e (Figure 4). Together, these images show that 4e and 13e induce M-phase arrest and interfere with microtubule formation in whole cells.

Conclusion

In summary, we identified N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)arylamide as a novel and proprietary small molecule scaffold for potential antitumor agents. Elucidating structure–activity relationships by subtraction from initial hit compound 4e (MCF-7 IC₅₀ = 560 nM) led to the discovery of 13e (MCF-7 IC₅₀ = 46 nM), a foundational compound for further study. Compound 13e (and related compounds) induced M-phase arrest in HeLa cells at 5 μM and inhibited tubulin polymerization in vitro at 10 μM, providing strong support for antimitotocutule activity as the primary mechanism of action. The NCI-60 screen demonstrated broad-spectrum antitumor activity and prompted further biological evaluation. Compound 13e was recently evaluated by the National Cancer Institute Developmental Therapeutics Program (NCI DTP) for acute toxicity in vivo, and 100, 200, and 400 mg/kg intraperitoneal (IP) doses were well tolerated in nontumor-bearing mice. Ongoing studies in collaboration with the NCI DTP will evaluate in vivo efficacy in hollow fiber assays. Extensive SAR studies and the development of a combinatorial library are accessible because compounds based on the N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)arylamide scaffold are readily synthesized with the CuAAC reaction. Our findings will facilitate the design and optimization of potent, cell-permeable antimitocutule agents.

Experimental Section

Purity of all samples are ≥95% as determined by HPLC or LC/HRMS.

2-(4-Methoxyphenyl)-N-((1-(3-phenoxybenzyl)-1H-1,2,3-triazol-4-yl)methyl)oxazole-4-carboxamide (C₂₇H₂₃N₅O₄, 13e). 2-(4-Methoxyphenyl)oxazole-4-carboxylic acid (11e, 0.951 g, 4.3 mmol) was suspended in anhydrous CH₂Cl₂ (12 mL) under argon. Oxalyl chloride (0.45 mL, 5.2 mmol) and N,N-dimethylformamide (20 μL) were added carefully to the mixture because of gas evolution. The reaction slowly turned to a light-yellow homogeneous solution over 3 h. The solution was concentrated in vacuo to give 2-(4-methoxyphenyl)oxazole-4-carbonyl chloride (1.0 g, 97%) as an off-white solid (0.788 g, 77%; mp 151–152 °C. ¹H NMR (300 MHz, CDCl₃) δ 8.06 (s, 1H), 7.82 (d, J = 8.5 Hz, 2H), 7.13 (bs, NH, 1H), 6.84 (d, J = 8.5 Hz, 2H), 4.15–4.07 (m, 2H), 3.72 (s, 3H), 2.15 (s, 1H). ¹³C NMR (126 MHz, CDCl₃) δ 161.82, 161.57, 160.40, 140.49, 136.44, 128.83, 128.29, 119.13, 114.26, 113.69, 71.17, 71.69, 55.37, 28.66. HRMS—FAB (m/z) [M + H]+ caked for C₂₇H₂₃N₅O₄, 527.0921; found, 527.0930.

2-(4-Methoxyphenyl)-N-(prop-2-ynyl)oxazole-4-carboxamide (12e, 300 mg, 1.17 mmol) and 1-(azidomethyl)-3-phenoxynenzo (290 mg, 1.29 mmol) were suspended in a 2:1 mixture of water and tert-butyl alcohol (4.7 mL total volume). Sodium ascorbate (0.12 mmol, 0.12 mL, 1 M) and copper(II) sulfate (0.012 mmol, 0.12 mL, 0.1 M) were added sequentially. After stirring for 4 days at room temperature, TLC analysis indicated complete consumption of the reactants. The reaction mixture was diluted with water (5 mL) and cooled on ice. The white precipitate was isolated by vacuum filtration and washed with cold water (3 × 5 mL) and cold diethyl ether (3 × 3 mL) to afford 506 mg (90%) of pure product (13e) as a white powder. TLC Rₛ = 0.42 (EtOAc); HPLC tᵣ = 6.82 min (9:1 hexanes:2-propanol); mp 119.1–119.4 °C. ¹H NMR (300 MHz, CDCl₃) δ 8.18 (s, 1H), 7.99–7.93 (m, 2H), 7.60 (bs, NH, 1H), 7.55 (s, 1H), 7.39–7.28 (m, 3H), 7.16–7.09 (m, 1H), 7.03–6.90 (m, 7H), 5.47 (s, 2H), 4.72 (d, J = 6.1 Hz, 2H), 3.88 (s, 3H). ¹³C NMR (151 MHz, CDCl₃) δ 161.83, 161.56, 160.84, 158.04, 156.36, 145.05, 140.26, 136.70, 136.29, 130.46, 129.85, 128.31, 127.79, 122.46, 122.27, 119.26, 119.18, 118.56, 114.28, 55.40, 53.84, 34.46. HRMS—FAB (m/z) [M + H]+ caked for C₂₇H₂₃N₅O₄, 482.1823; found, 482.1803.

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Supporting Information Available: Materials and methods, characterization data for all compounds, cell proliferation curves, cell cycle arrest profiles, and COMPARE analysis results. This material is available free of charge via the Internet at http://pubs.acs.org.

References


