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Chroman-4-one- and Chromone-Based Sirtuin 2 Inhibitors with Antiproliferative Properties in Cancer Cells

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Supporting Information

ABSTRACT: Sirtuins (SIRTs) catalyze the NAD⁺-dependent deacetylation of N°-acetyl lysines on various protein substrates. SIRTs are interesting drug targets as they are considered to be related to important pathologies such as inflammation and aging-associated diseases. We have previously shown that chroman-4-one acts as potent and selective inhibitors of SIRT2. Herein we report novel chroman-4-one and chromone-based SIRT2 inhibitors containing various heterofunctionalities to improve pharmacokinetic properties. The compounds retained both high SIRT2 selectivity and potent inhibitory activity. Two compounds were tested for their antiproliferative effects in breast cancer (MCF-7) and lung carcinoma (A549) cell lines. Both compounds showed antiproliferative effects correlating with their SIRT2 inhibition potency. They also increased the acetylation level of α-tubulin, indicating that SIRT2 is likely to be the target in cancer cells. A binding mode of the inhibitors that is consistent with the SAR data was proposed based on a homology model of SIRT2.

INTRODUCTION

Sirtuins (SIRTs) compose class III of lysine deacetylases (KDACs). There are seven conserved human isoforms (SIRT1–SIRT7) with different subcellular locations. The enzymes catalyze the reversible deacetylation of lysine residues both on histones (H1, H3, H4) and nonhistone proteins, e.g., p53, p65, PGC-1α, PPARγ, FOXO, NFκB, and α-tubulin. The deacetylation reaction requires nicotinamide adenine dinucleotide (NAD⁺) as cosubstrate, and results in the formation of the deacetylated protein substrate, O-acetyl-ADP-ribose, and nicotinamide, which is the endogenous inhibitor of the sirtuins. In addition to the deacetylation, also mono-ADP-riboseyl transferase activity and removal of long-chain fatty acyl groups from lysine residues have been reported for SIRT6. Mono-ADP-riboseyl transferase activity is the only effect observed for SIRT4. Recently, Du et al. discovered lysine demalonylation and desuccinylation activities of SIRT5, which later was followed by reports by Zhao and co-workers regarding deglutarylation from lysine residues as a function of SIRT5.

Because of the broad spectrum of substrates, SIRTs have been implicated as regulators in a range of physiological processes, including metabolism, cell survival and apoptosis, gene expression, and DNA repair. Therefore, the enzymes have been proposed to be involved in pathologies such as inflammation and aging-associated diseases, e.g., cancer, diabetes, and neurodegeneration (e.g., Alzheimer’s, Huntington’s, and Parkinson’s disease). The potent SIRT1 inhibitor selisistat (36 (Ex-527), Chart 2) reduces Huntington’s disease pathology and has been in phase II clinical studies. SIRT2, which is the focus of the present study, is predominantly located in the cytoplasm but is enriched in the nucleus during mitosis. Beside the deacetylation of histone H4, the enzyme is also involved in the deacetylation of nonhistone substrates such as α-tubulin, FOXO, p65, p50, and p53. Hence, the enzyme is proposed to be involved in the regulation of the cell cycle.

SIRT2 is highly expressed in the brain, and inhibition appears to be neuroprotective as two SIRT2 selective inhibitors have been shown to counteract progression of Huntington’s and Parkinson’s disease. Regarding its role in oncogenesis, there are contradictory reports in the literature whether SIRT2 is a tumor suppressor or promoter. Down-regulation of SIRT2 reduced the cell proliferation in glioma cells, HeLa cells, and liver and pancreatic carcinomas. Inhibition of SIRT2 by selective inhibitors such as AGK-2, Chart 2 and a 10,11-dihydro-SH-dibenz[b,f]azepine derivative have been shown to induce apoptosis in C6 glioma cells and MCF-7 breast cancer cells, respectively. Other small-molecule inhibitors are described in recent studies.

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SIRT2 inhibitors have shown to reduce cancer proliferation via the increase in p53 acetylation in nonsmall-cell lung cancer cells (A549 and H1299). Therefore, SIRT2 has been considered to be an interesting target for cancer drug development.

Recently, we showed that trisubstituted 2-alkyl-chroman-4-ones can serve as selective SIRT2 inhibitors with IC\textsubscript{50} values in the low micromolar range. Two of the most potent inhibitors are shown in Chart 1.

The structure–activity relationship (SAR) study revealed that electron-withdrawing groups on the aromatic ring of the bicycle, the carbonyl group, as well as an alkyl side chain in the 2-position are crucial for potent inhibitors. The SAR study also disclosed an exceptionally close relationship between the presence of all features mentioned above and the inhibitor potency as even minor modifications resulted in a severe loss of activity. Analysis of the individual enantiomers of 1 showed that the stereoisomers had only small differences in inhibitory activities, with (S)-1 being slightly more potent (Chart 1).

However, the high lipophilicity of the published chroman-4-ones limits their use in more advanced biological in vivo and in vitro tests. Herein, we report chroman-4-one analogues based on lead compounds 1 and 2 as potential SIRT2 inhibitors with increased hydrophilicity. The hydrophilicity was increased by the introduction of heterofunctional groups such as terminal fluorine in a microwave-heated reaction, 34 providing the deprotected chroman-4-ones 6a–c in 16–78% yield over three steps. Removal of the silyl protecting group of 5a and 5b with the more commonly used tetrabutylammonium fluoride (TBAF) in THF surprisingly yielded the ring opened products 7a and 7b (Scheme 2). No formation of the ring-opened byproduct was observed for 5c. Treatment of the hydroxyl derivatives 6a and 6b with TBAF also resulted in the formation of ring opened products. The byproduct formation is likely to be attributed to the basicity of the fluoride ion in organic solvents. In separate experiments, it was however found

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**RESULTS AND DISCUSSION**

**Chemistry.** The key reaction in the synthesis of the biologically evaluated compounds is the assembling of the chroman-4-one scaffold. The general synthetic strategy for the formation of chroman-4-ones 6a–i is shown in Scheme 1 and involves the base-promoted aldol condensation between a substituted 2’-hydroxyacetophenone and an aldehyde, followed by an intramolecular oxo-Michael ring closure reaction. Commercially available aldehydes (3a, 3d–g) were used as precursors for the desired aldehydes, whereas alcohols 3b and 3c were synthesized via monoprotection of commercially available diols using NaH and TBDMS-Cl according to a procedure reported by McDougal et al. The aldehydes (4a–g) were obtained via Swern or Dess–Martin oxidation and could be directly used in the next step without any further purification. For the ethylene glycol based aldehyde 4d, the ordinary workup procedure involving addition of water and EtOAc had to be changed to a nonaqueous workup due to its high water solubility.

The chroman-4-ones 5a–c and 6d–i were synthesized in moderate to good yields by heating 2’-hydroxyacetophenones and the appropriate aldehydes in a microwave reactor for 1 h in ethanol using NaN\textsubscript{3},N-diisopropylamine (DIPA) as base. The TBDMS-protection group of 5a–c was removed using electrophilic fluorine in a microwave-heated reaction, providing the deprotected chroman-4-ones 6a–c in 16–78% yield over three steps. Removal of the silyl protecting group of 5a and 5b with the more commonly used tetrabutylammonium fluoride (TBAF) in THF surprisingly yielded the ring opened products 7a and 7b (Scheme 2). No formation of the ring-opened byproduct was observed for 5c. Treatment of the hydroxyl derivatives 6a and 6b with TBAF also resulted in the formation of ring opened products. The byproduct formation is likely to be attributed to the basicity of the fluoride ion in organic solvents. In separate experiments, it was however found

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**Scheme 1. General Synthetic Scheme towards the Substituted Chroman-4-ones 6a–i**

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Reagents and conditions: (a) (i) (COCl)\textsubscript{2}, DMSO, THF, −78 °C, 30 min, (ii) appropriate alcohol, −78 °C, 30 min, (iii) Et\textsubscript{3}N, −78 °C → room temp, 15 min, or Dess–Martin periodinane, CH\textsubscript{2}Cl\textsubscript{2}, room temp; (b) appropriate 2’-hydroxyacetophenone, DIPA, EtOH, MW, 170 °C, 1−2 h; (c) Selectfluor, MeOH, MW, 150 °C, 30 min. Commercially available hexanal (4h) was used.
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that the byproduct was not formed when triethylamine was used as base.

The ester analogues of 6a and 6b were prepared according to the synthetic route outlined in Scheme 3. \( \delta \)-Valerolactone and \( \gamma \)-butyrolactone were ring-opened under basic conditions in MeOH. Alcohol oxidation provided aldehydes \( \gamma \) the synthetic route outlined in Scheme 3. Reacting 2-hydroxyacetophenones with

\[ \text{Scheme 2. Synthesis of Ring-Opened Derivatives Using TBAF} \]

Reagents and conditions: (a) TBAF, THF, room temp, overnight.

\[ \text{Scheme 3. Synthesis of Ester Derivatives of 2,6,8-Trisubstituted Chroman-4-ones} \]

Reagents and conditions: (a) Et3N, MeOH, room temp, 18 h; (b) SO\(_2\)-pyridine, Et3N, DMSO, room temp, 14 h, or (i) (COCl)\(_2\), DMSO, THF, \(-78^\circ\text{C}\), 30 min, (ii) appropriate alcohol, \(-78^\circ\text{C}\), 30 min, (iii) Et3N, \(-78^\circ\text{C}\) \(\rightarrow\) room temp, 15 min; (c) 3'-bromo-5'-chloro-2'-hydroxyacetophenone, piperidine or DIPA, EtOH, 170 \(\circ\text{C}\), 0.5–1 h.

Eventually, the prolongation of the spacer between the chroman-4-one scaffold and the heterocycle to propylene enabled the synthesis of related analogues of the phenethyl-heterocycle to propylene bearing hydrogen-bonding groups further away from the sca

According to the above-described monocyclic hetero-functionalities, bicyclic groups were introduced to move the hydrogen-bonding groups further away from the scaffold. Two different ring systems were chosen, i.e., quinolin-6-yl and 3,4-dihydro-2(1H)-quinolinone-6-yl. The starting material 6-bromo-3,4-dihydro-2(1H)-quinolinone was prepared in analogy to the procedure reported by Tietze et al. and Zaragoza et al. Reaction of the bromo-substituted bicyclic systems with acetal-protected acrolein in a Heck reaction yielded 18a–b (Scheme 7). Catalytic hydrogenation and deprotection of the acetal under acidic conditions furnished the desired aldehyde

be synthesized in analogy to the standard route outlined in Scheme 1 starting from commercially available alcohols as precursors (Scheme 5). However, neither Swern oxidation of 3-morpholinopropan-1-ol nor the use of other oxidizing agents such as Dess–Martin periodinane, TEMPO, TPAP, or CrO\(_3\) resulted in the desired aldehyde 13. Finally, 13 was obtained by conjugate addition of morpholine to acrolein (Scheme 5). Applying the standard procedure for approaching target compound 14a was unsuccessful as well as attempts via preformation of the aldol intermediate using of lithium disopropylamide (LDA). Attempts to approach the aliphatic heterocycles containing chroman-4-ones via a substitution reaction of a terminal hydroxyl group failed due to the unsuccessful reaction of the acetophenone and aldehyde 15. None of the approaches resulted in the formation of the desired products.

Eventually, the prolongation of the spacer between the chroman-4-one scaffold and the heterocycle to propylene enabled the synthesis of related analogues of the phenethyl-substituted chroman-4-one 2. The synthetic pathway toward the derivatives is outlined in Scheme 6. Compounds 17a and 17b were finally prepared from the mesylated chroman-4-one 16 via a microwave-assisted substitution reaction using morpholine and piperidine.

In addition to the above-described monocyclic hetero-functionalities, bicyclic groups were introduced to move the hydrogen-bonding groups further away from the scaffold. Two different ring systems were chosen, i.e., quinolin-6-yl and 3,4-dihydro-2(1H)-quinolinone-6-yl. The starting material 6-bromo-3,4-dihydro-2(1H)-quinolinone was prepared in analogy to the procedure reported by Tietze et al. and Zaragoza et al. Reaction of the bromo-substituted bicyclic systems with acetal-protected acrolein in a Heck reaction yielded 18a–b (Scheme 7). Catalytic hydrogenation and deprotection of the acetal under acidic conditions furnished the desired aldehyde
19a (Scheme 7). Surprisingly, under the mild reducing conditions (H₂-balloon, 10% Pd/C, room temp) chosen to reduce the aliphatic double bond in 18b also the quinoline moiety was reduced to yield the corresponding 1,2,3,4-tetrahydroquinoline. When Pd/C and 1,4-cyclohexadiene was used as reducing agent, only reduction of the aliphatic double bond occurred, and after treatment with acid, the desired aldehyde (19b) was obtained. The aldehydes were then reacted under standard conditions with 3'-bromo-5'-chloro-2'-hydroxyacetophenone to yield 20a−b in moderate yields.

The tetrasubstituted chromones 21−25 were synthesized as illustrated in Scheme 8. The monobrominated chroman-4-one 21 was obtained by reaction of 2 with CuBr₂. Treatment of 21 with NaN₃ in DMSO resulted in the formation of amine 22, which was acetylated with acetyl chloride in pyridine to form 23. A SmI₂-mediated Reformatsky type reaction using tosyl cyanide as described earlier by Ankner et al. was successfully applied to introduce a nitrile moiety in the 3-position, and subsequent oxidation with DDQ in dioxane yielded 3-cyano-chromone 24. Further reduction of the nitrile group by means of DIBAL-H furnished enaminone 22 in 66% yield.

Molecular Modeling. Mode of Action of Sirtuins and Inhibitor Binding. Sirtuins contain a conserved enzymatic core comprising a Rossmann fold domain and a small domain containing a three-β-stranded zinc binding motif. The Rossmann fold contains six parallel β-strands forming a central β-sheet which is sandwiched between α-helices (number dependent on SIRT isoform) on either side of the β-sheet. Between these domains the binding sites of NAD⁺ and the acetylated peptide substrate are located. The NAD⁺ binding site can be formally divided into the subpockets A (adenine binding site), B (ribose binding site), and C (nicotinamide binding site). Binding of the peptide substrate and NAD⁺ is proposed to take place in a sequential manner. Binding of the peptide substrate induces the cleft between the two domains to close, and upon NAD⁺ binding the cofactor binding loop gets ordered. The presence of an acetyl lysine peptide promotes a strained, productive NAD⁺ conformation, which is required for the deacetylation reaction to proceed. This conformation positions the nicotinamide moiety of NAD⁺ in the C-pocket and brings the ribose ring in vicinity of the acetyl group in the peptide substrate.
The C-pocket is the presumable binding site for potent small-molecular SIRT1/2 inhibitors (Chart 2) such as $30^{22}$, thieno[3,2-$d$]pyrimidine-6-carboxamides ($31^{47}$), 3-arylidenediindolin-2-ones ($32^{48}$), salermide ($33^{49}$), cambinol ($34^{50}$), and splitomicin analogues ($35^{51}$) and $36^{52}$. We therefore wanted to investigate whether this pocket could be a feasible binding site also for our compounds.

Homology Modeling of Human SIRT2. Four crystal structures of SIRT2 are currently available.$^{53-55}$ Two of these are apo-structures (PDB codes 1J8F and 3ZGO (3ZGO is a rerefinement of the human SIRT2 apoenzyme 1J8F)$^{53,54}$), lacking both peptide substrate and NAD$^+$ in their catalytic site. Their structures differ considerably compared to structures where peptide substrate and/or NAD$^+$ are bound. Another SIRT2 structure in complex with ADP-ribose (ADPr) was recently solved (3ZGV)$^{54}$. ADPr is similar to NAD$^+$ in structure; it binds in the NAD$^+$ binding cleft and thereby induces the conformational change which closes the active site crevice around ADPr in the Rossmann-fold domain. The fourth structure (4L3O) is a complex of SIRT2 with inhibitor S2iL5, which is a macrocycle binding from the outside into the peptide binding channel.$^{55}$ Because the structure with ADPr (3ZGV)$^{54}$, ADPr is similar to NAD$^+$ in structure; it binds in the NAD$^+$ binding crevice and thereby induces the conformational change which closes the active site crevice around ADPr in the Rossmann-fold domain. The fourth structure (4L3O) is a complex of SIRT2 with inhibitor S2iL5, which is a macrocycle binding from the outside into the peptide binding channel.$^{55}$ Because the structure with ADPr (3ZGV)$^{54}$, ADPr is similar to NAD$^+$ in structure; it binds in the NAD$^+$ binding crevice and thereby induces the conformational change which closes the active site crevice around ADPr in the Rossmann-fold domain. The fourth structure (4L3O) largely differs from the small molecular chroman-4-one-based inhibitors. Of the two structures considered, the SIRT3/NAD$^+$/($S$)-36$^{55}$ structure (PDB 4BV3) binds NAD$^+$ in a nonproductive mode, with the nicotinamide moiety rotated $180^{\circ}$ relative to the C-pocket and instead positioned in the peptide binding channel. Like ($S$)-36$^{55}$ and ($S$)-37$^{56}$, the chroman-4-ones do not appear to be peptide substrate competitive inhibitors (data not shown), therefore the SIRT1/NAD$^+$/($S$)-37 complex (PDB code 4I5I) was chosen as a template for homology modeling.$^{56}$ Models were constructed that included a lysine residue from a Sir2-p53 peptide—NAD$^+$ complex (2H4F)$^{46}$ together with NAD$^+$ and inhibitor (4I5I). The homology modeling was performed using the MOE software (v. 2012.10, Chemical Computing Group Inc.: Montreal).

Chart 2. Structures of SIRT1/2 Inhibitors Known to Occupy the C-Pocket of the NAD$^+$-Binding Site and Our Chroman-4-one-Based Inhibitor 6f

Scheme 8. Synthesis towards Tetrasubstituted Chromone Derivatives

"Reagents and conditions. (a) CuBr$_2$, CHCl$_3$/EtOAc, 2 h, reflux; (b) NaN$_3$, DMSO, 70 min, room temp; (c) AcCl, pyridine, room temp, overnight; (d) Sm$_2$, KHMD$_5$, TsCN, THF, $-78^{\circ}$C $\rightarrow$ room temp, cis/trans 29:71; (e) DDQ, dioxane, room temp, 12 h; (f) DIBAL-H, CH$_2$Cl$_2$, $-78^{\circ}$C, 3 h."
A multiple sequence alignment was performed in ClustalW (v. 2.1)⁵⁷ using the template (SIRT1 human, 4I5I (Q96EB6)),⁶⁸ the main target (SIRT2 human, Q8IXJ6), and the human SIRT3 sequence (Q9NTG7). The alignment was fine-tuned to improve the final homology model (Figure S1, Supporting Information). A detailed description of the homology modeling procedure is given in the Supporting Information. The force field used in the homology modeling in this study was Amber12:EHH with R-Field solvation, as implemented in the MOE software.

During the construction of the homology model, inhibitor 6f was positioned in the C-pocket close to the location of 37 in the SIRT1 structure in order to achieve more information regarding the inhibitor–enzyme interactions. NAD⁺ was included in the modeling procedure with its geometry kept from the SIRT1 structure, i.e., in its nonproductive mode. The lysine residue from a Sir2-p53 peptide from the SIRT1 structure, i.e., in its nonproductive mode. The included in the modeling procedure with its geometry kept conserved water molecule W17 (Figure 1).⁵²,⁵⁴,⁵⁸ There is also shown (see Ramachandran plots in Figure S2 in the Supporting Information). In the resulting homology model the chroman-4-one scaffold of inhibitor 6f is buried in a hydrophobic and well-defined binding pocket. The carbonyl oxygen of 6f forms a hydrogen bonding interaction with a conserved water molecule W17 (Figure 1).⁵²,⁵⁴,⁵⁸ There is also a halogen bonding interaction from the chloride in the 6-position to the backbone carbonyl of His187 with a distance of 3.7 Å (Cl···O=) and an angle of 163.5° (C–Cl···O=), which is an acceptable geometry.⁶⁰ The bromide in the 8-position is located in a hydrophobic environment surrounded by Leu103, Phe119, Leu138, and Phe190. In addition, Phe96 is favorably positioned for π–π interaction with the halogen substituted aromatic ring of 6f⁶⁰ although this interaction is not geometrically optimal as the rings are arranged in a shape which is in between a parallel displacement and a face-to-edge arrangement (r = 5.4 Å, θ = 53.7°, ω = 35.1°, for definition see Figure S3 in Supporting Information).⁶¹ The 2-(pyridin-3-yl)ethyl moiety is positioned in a rather narrow hydrophobic channel (Figure 1), which is directed toward the surrounding solution. The pyridine nitrogen of 6f forms a hydrogen bond with Gln142 but could instead easily interact with surrounding water molecules outside the enzyme (Figure 1a,b).

**Evaluation of Inhibitory Activity.** The inhibitory effect of the synthesized chroman-4-one/chromones on the activity of SIRT2 was evaluated using a fluorescence-based assay. Table 1 summarizes the results from the SIRT2 inhibition assay of the trisubstituted chroman-4-ones. For potent inhibitors, IC₅₀ values were determined, and these compounds were also tested against SIRT1 and SIRT3. In general, highly potent inhibitors showed to be selective for the SIRT2 subtype (for SIRT1 and SIRT3 inhibition data, see Table S3 in Supporting Information).

The SIRT2 inhibition data for the tetrasubstituted chromones are summarized in Table 2. These chromone-based derivatives are moderately potent and selective SIRT2 inhibitors (Table 2).

Potent inhibitors were also tested for their inhibitory effect on members of other classes of HDACs. The test confirmed that the compounds exclusively inhibit the class III of lysine deacetylases (HDAC inhibition <10% at 200 μM, data not shown).

**Physicochemical properties of this new series of chroman-4-one/chromone-based inhibitors were calculated (Table S4, Supporting Information). The results indicate that the structural modifications did lead to less lipophilic compounds with improved physicochemical properties. As illustrated in Table 3, the potent inhibitors of the new series have similar inhibitory activity as lead compounds 1 and 2, however they exhibit more attractive physicochemical properties such as decreased clogP and clogD-values as well as a larger PSA (Table 3). Among the synthesized compounds, derivatives 6f and 12a were chosen for evaluation of a potential antiproliferative effect (see below Figure 3). Although the methyl ester 9b is the most potent inhibitor and 9a is as active
as 12a, the methyl ester group is prone to hydrolysis in the cell-based assay, yielding the biologically inactive carboxylic acids analogues 10a and 10b, therefore 9a and 9b were not further investigated.

Table 1. Results from Evaluation of Trisubstituted Chroman-4-ones in a SIRT2 Inhibition Assay

<table>
<thead>
<tr>
<th>No.</th>
<th>R²</th>
<th>Inhib (%)</th>
<th>IC₅₀ (μM)</th>
<th>No.</th>
<th>R²</th>
<th>Inhib (%)</th>
<th>IC₅₀ (μM)</th>
</tr>
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<tr>
<td>rac-1</td>
<td>-</td>
<td>88 ± 0.9</td>
<td>4.3</td>
<td>10a</td>
<td>-</td>
<td>6.8 ± 1.5</td>
<td>n.d.</td>
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<tr>
<td>2</td>
<td>-</td>
<td>81 ± 0.7</td>
<td>6.8</td>
<td>10b</td>
<td>-</td>
<td>7.6 ± 1.6</td>
<td>n.d.</td>
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<tr>
<td>6a</td>
<td>-</td>
<td>18 ± 1.1</td>
<td>n.d.</td>
<td>11a</td>
<td>-</td>
<td>0.2 ± 4.8</td>
<td>n.d.</td>
</tr>
<tr>
<td>6b</td>
<td>-</td>
<td>52 ± 0.9</td>
<td>n.d.</td>
<td>11b</td>
<td>-</td>
<td>39 ± 0.9</td>
<td>n.d.</td>
</tr>
<tr>
<td>6c</td>
<td>-</td>
<td>69 ± 0.5</td>
<td>n.d.</td>
<td>11c</td>
<td>-</td>
<td>23 ± 1.8</td>
<td>n.d.</td>
</tr>
<tr>
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<td>33 ± 2.0</td>
<td>n.d.</td>
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<td>-</td>
<td>39 ± 0.9</td>
<td>n.d.</td>
</tr>
<tr>
<td>6e</td>
<td>-</td>
<td>74 ± 0.5</td>
<td>n.d.</td>
<td>11e</td>
<td>-</td>
<td>53 ± 1.4</td>
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<td>6f</td>
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<td>86 ± 1.9</td>
<td>3.7</td>
<td>12a</td>
<td>-</td>
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<td>12b</td>
<td>-</td>
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<tr>
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<td>n.d.</td>
<td>17a</td>
<td>-</td>
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<tr>
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<td>1.8</td>
<td>17b</td>
<td>-</td>
<td>40 ± 2.8</td>
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<tr>
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<td>n.d.</td>
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</table>

“SD, standard deviation (n = 3). Inhibition at 200 μM inhibitor concentration. Suramin was used as reference compound in the assay. IC₅₀ (95% confidence interval). IC₅₀ values were determined for compounds showing >80% inhibition of SIRT2 at 200 μM concentration or compounds evaluated in the cell proliferation assay. n.d. = not determined. The SIRTAinty assay was used for the determination.
Structure–Activity Relationships. In this study, we have focused on chroman-4-ones/chromones with increased hydrophilicity. This was achieved by the introduction of aliphatic and aromatic mono/bicyclic moieties with hydrogen-bonding groups in the 2-position of the chromones as well as the implementation of hydrogen bonding groups in the 3-position of the chromones. These changes were done to improve the inhibition of SIRT2 but also to obtain information about space limitations caused by the introduction of bulkier groups.

The substituent in the 2-position is crucial for SIRT2 inhibition because 5-bromochroman-4-one lacking a substituent in the 2-position does not show any inhibition (data not shown), while the corresponding analogue 6b, which has a pentyl group in the 2-position, shows an inhibitory activity of 70% (Table 1). Replacement of the pentyl side chain in lead compound 1 with a more polar ethylene glycol side chain (6d) resulted in a significant decrease in activity (33% inhibition) as did the introduction of a terminal hydroxyl group (6a, 18% inhibition). However, by increasing the length of the linker between the OH-group and the scaffold (6b and 6c), some activity could be retained (Table 1). Still, 6c (67% inhibition) is less potent then the lead compound ((rac)-1, 88%). This indicates that highly polar side chains (6d) and hydrogen bond donating groups are not favorable with a chain length up to five atoms. This observation can be explained by the homology model, which shows that five out of seven amino acids surrounding this channel are hydrophobic (Ile93, Pro94, Leu103, Leu138, and Phe143, Figure 1a and Figure S1 in the Supporting Information). One of two hydrophilic amino acids (Asp170) is rotated away from the substituent in the 2-position while the other (Gln142) is directed toward the aqueous solution, which might explain the enhanced activity with increasing length of the spacer for alcohols 6a–c. Replacement of the phenyl ring in 2 with a pyridyl moiety (6e–g) resulted in compounds with similar activity and improved solubility. The 3-pyridyl substituted chroman-4-one (6f) was with 86% inhibition most potent compared to the 2- and 4-pyridyl analogues 6e and 6g. Modeling results showed that the pyridyl moiety of 6f has an optimal geometry to form a hydrogen bond with Gln142, which is located at the end of the hydrophobic channel toward the aqueous solution (Figure 1b). This hydrogen bonding interaction can also be observed for the ester functionality in 9a and 9b, the latter being one of the most potent inhibitors with an IC50 value of 2.0 μM. As earlier mentioned, esters are prone to hydrolysis under physiological conditions and therefore also the corresponding acids were investigated. However, the carboxylic acids 10a and 10b were completely inactive, which could be attributed to carbonate formation at physiological pH. Negatively charged groups are unfavorable in the lipophilic and narrow channel accommodating the R2-substituent. The replacement of the methyl ester in 9a–b with a methyl amide (11a and 11b) dramatically lowered the activity. Also replacement of the methyl amide with the bulkier isopropyl (11c) or benzyl amides (11d) gave no increase in inhibitory potency. Only the dimethyl amide 11e was slightly more potent, with 53% inhibition compared to 39% for the monomethyl amide. The secondary amides (11a–d) can act both as hydrogen bond accepting and donating group, and here it seems as the presence of an NH-group decreases the activity. However, all amide analogues are not as active as the methyl esters (9a–b). An explanation for this could be that an NH-group is less favorable in the lipophilic environment than the less hydrophilic single bonded oxygen of the ester. This statement was supported in docking studies22,60 of 9b and 11b, where the O- and N-methyl groups are positioned in a small hydrophobic pocket rather than toward the aqueous solution (Figure 2). Thereby, the single-bonded oxygen in the ester and the NH-moiety in the amide are oriented toward the hydrophobic site, which makes the more polar amide

Table 2. Results from Evaluation of the Tetrasubstituted Chromones in a SIRT2 Inhibition Assay

<table>
<thead>
<tr>
<th>no.</th>
<th>R3</th>
<th>inhib (%)</th>
<th>IC50 (μM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>NH1</td>
<td>79 ± 1.5</td>
<td>nd</td>
</tr>
<tr>
<td>23</td>
<td>NHAc</td>
<td>81 ± 0.9</td>
<td>28.7 (21.4–38.5)</td>
</tr>
<tr>
<td>24</td>
<td>CN</td>
<td>50 ± 19</td>
<td>nd</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

“SD, standard deviation (n = 3). bInhibition at 200 μM inhibitor concentration. cIC50 (95% confidence interval). dIC50 value was determined for compounds showing >80% inhibition. end = not determined.

Table 3. Data of Calculated Physicochemical Properties of Lead Compounds 1 and 2 and of 6f, 9a–b, and 12a from the New Series

<table>
<thead>
<tr>
<th>no.</th>
<th>IC50 (μM)</th>
<th>MW</th>
<th>ACDlogP</th>
<th>ACDlogD pH 7.4</th>
<th>PSA (Å²)</th>
<th>HBDa</th>
<th>HBAa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.3</td>
<td>311.6</td>
<td>5.60</td>
<td>5.60</td>
<td>27.4</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>6.8</td>
<td>365.7</td>
<td>5.57</td>
<td>5.57</td>
<td>27.4</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>6f</td>
<td>3.7</td>
<td>366.6</td>
<td>4.19</td>
<td>4.18</td>
<td>37.6</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>9a</td>
<td>9.6</td>
<td>347.6</td>
<td>3.36</td>
<td>3.36</td>
<td>54.4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>9b</td>
<td>2.0</td>
<td>361.6</td>
<td>3.77</td>
<td>3.77</td>
<td>54.4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>12a</td>
<td>12.2</td>
<td>371.6</td>
<td>3.69</td>
<td>3.69</td>
<td>61.0</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

“Number of hydrogen bond donors. aNumber of hydrogen bond acceptors.

Figure 2. Docked chroman-4-one analogues 9b (red) and 11b (green) in the SIRT2 homology model. The green part of the surface is hydrophobic while the purple is hydrophilic. The carbonyl oxygens are forming hydrogen bonds with the glutamine residue Gln142, and the methyl groups are positioned in a small hydrophobic pocket. The polar hydrogen on the amide is pointing toward a hydrophobic region. Only the water molecule interacting with the carbonyl group in the chroman-4-ones (W17) is shown.
unfavorable compared to the ester. Compound 11e is still less active than 9b, which could be explained by the steric bulk of the dimethyl amide in the narrow tunnel.

The oxadiazole derivative with an ethylene linker (12a, IC\textsubscript{50} = 12.2 μM) was equipotent to the corresponding methyl ester. Surprisingly, the bioisosteric replacement of the methyl ester moiety of 9b with an oxadiazole group (12b) resulted in lower potency. Docking studies showed that 12a can adopt a similar binding pose as the ester whereas the methyl group of the longer oxadiazole 12b did not fit in the binding channel. The morpholine- and piperidine-substituted analogues 17a and 17b showed 17% and 40% inhibition, respectively. The morpholine and piperidine moieties are rather bulky, and the extended spacer places the groups further away from the scaffold and closer to the narrow part of the channel. Beside this, piperidine and morpholine are charged at pH 7.4, which seems unfavorable in the hydrophobic binding pocket. The chroman-4-one derivatives with the quinolinone and quinoline moieties (20a and b) were moderate inhibitors with 59% and 56% inhibition, respectively. These results are consistent with a previously published indolyl-substituted derivative\textsuperscript{32} which had 53% inhibitory activity. The rather narrow hydrophobic channel accommodating the side chain seems to be large enough to accommodate monocyclic ring systems rather than the large bicyclic moieties. Interestingly, the 6-bromo-8-chloro-chroman-4-one derivative 6i (IC\textsubscript{50} 1.8 μM) showed twice the activity of racemic 1 (IC\textsubscript{50} 4.3 μM), which strengthens the hypothesis of a halogen bonding interaction between the halide in the 6-position and the backbone carbonyl. A bromide is a better halogen bonding group than chloride, and therefore 6i was supposed to be more active than lead compound 1.

The chromones (Table 2) with an additional substituent in the 3-position showed generally only moderate inhibitory activity (50–81%). The acetamide substituted phenethylchromone 23 was the best inhibitor, with 81% inhibition and an IC\textsubscript{50} value of 29 μM. The introduction of the small

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**Figure 3.** SIRT2 inhibitors reduce A549 (left) and MCF-7 (right) cancer cell proliferation. The cells were treated with 0–100 μM of 6f and 12a. Cell proliferation was determined by a sulforhodamine B assay. The results are shown as mean ± SEM of two to three independent experiments. The asterisks indicate significant differences (* P < 0.05, *** P < 0.001 when compared to controls).

**Figure 4.** Effects of SIRT2 inhibitors on α-tubulin acetylation. MCF-7 cells were treated for 6 h (left panel) or 18 h (right panel) with 40 nM Trichostatin A plus indicated concentrations of 6f or 12a. The results are shown as mean ± SEM of three independent experiments. The asterisks indicate significant differences (* P < 0.05, *** P < 0.001 when compared to controls). The representative Western blots are shown below.
heterofunctional side chain on the flat ring system did not result in the desired increase in potency via additional hydrogen bonding interactions.

**Evaluation of Antiproliferative Properties.** We have previously shown that SIRT1/2/3 pan-inhibitors can cause antiproliferative effects in MCF-7 breast cancer and A549 lung cancer cell lines. Literature reveals that also SIRT2 inhibitors have been shown to have an antiproliferative effect in MCF-7 breast cancer cells and A549 lung cancer cells. We therefore wanted to study whether the novel compounds could achieve similar effects. Two potent inhibitors (6f, 12a) with acceptable physicochemical profiles were chosen for testing in cancer cell proliferation assays. These two human cancer cell lines were exposed to increasing concentrations of 6f and 12a, and the cell proliferation was measured using a sulforhodamine B assay. Both compounds had a strong inhibitory effect on cancer cell growth (Figure 3). Compound 6f showed a significant antiproliferative effect already at 10 μM concentration, and under microscopic evaluation there were no living cells visible after 48 h with higher concentrations (≥50 μM) of 6f (data not shown).

SIRT2 is known to deacetylate α-tubulin. To confirm the functionality of 6f and 12a as SIRT2 inhibitors in a cellular environment, MCF-7 cells were treated with these compounds and subjected to Western blot analysis of α-tubulin acetylation levels. After 6 h, treatment with 100 μM 6f had produced a drastic increase in acetylated α-tubulin and lower concentrations of 6f had weaker effects to the same direction (Figure 4). After 18 h, all cells treated with 100 μM 6f had died and no sample could be obtained for Western blotting. Nevertheless, 6f gave significant levels of inhibition of α-tubulin deacetylation at lower concentrations at this time point. Treatments with 50 and 100 μM of 12a decreased total α-tubulin after 18 h. When compared to total α-tubulin, there was a clear, albeit nonsignificant trend toward increased α-tubulin acetylation in these samples.

Flow cytometric cell cycle analysis was performed in order to examine the basis for the antiproliferative effects of 6f and 12a. Treatment of MCF-7 or A549 cells for 18 h with 100 μM 12a resulted in cell cycle arrest, as there was a significant increase in the fraction of cells in G1/G0 phase and a significant decrease in the fraction of cells in DNA synthesis phase (Figure 5). Furthermore, the fraction of A549 cells in G2 phase decreased. Treatment with 50 μM 6f also resulted in similar cell cycle arrest in A549 cells (significant) and MCF-7 cells (trend) (Figure 5). No apoptosis was observed in any of the samples (data not shown). The G1/G0 arrest is not necessarily resulting from increased acetylation of α-tubulin but may result from some other SIRT2-mediated event, and similar observations have been found in the literature.

**CONCLUSION**

A series of chroman-4-ones carrying heterofunctional groups in the side chain in the 2-position together with four tetrasubstituted chromones were synthesized in good yields using efficient synthetic methods. Compared to the previously published chroman-4-ones, calculations of the physicochemical properties indicate that the new compounds show improved pharmacokinetic properties. Analogues carrying hydrogen bond accepting groups, e.g., pyridyl or ester moieties, were highly potent and selective SIRT2 inhibitors with low micromolar IC50 values. Two compounds (6f and 12a) were chosen for investigation of their effects on cell proliferation in MCF-7 breast cancer and A549 lung cancer cells. Both compounds showed antiproliferative effects which correlate with their SIRT2 inhibition potency. SIRT2 is likely to be the target in the cancer cell lines, as we could show that the degree of acetylation of α-tubulin increased in a dose-dependent manner. A homology model of SIRT2 based on a SIRT1 crystal structure was built, and docking studies clarified the binding mode of the chroman-4-one-based inhibitors. The proposed binding mode of our compounds was similar to other reported SIRT inhibitors in that they occupy the nicotinamide binding site and prevent NAD+ to bind in a catalytically active conformation. The docking studies contributed also to a deeper understanding of the SAR data. However, the reasons behind the isoform selectivity of the chroman-4-ones are still unclear but work is ongoing to get an understanding of the selectivity profile and to verify the binding mode.

**EXPERIMENTAL SECTION**

**General.** All reactions were carried out using magnetic stirring under ambient atmosphere if not otherwise noted. Room temperature corresponds to a temperature interval from 20 to 21 °C. All starting materials and reagents were obtained from commercial producers and were used without prior purification. Solvents were generally used as supplied by the manufacturer. Microwave reactions were carried out using a Biotage Initiator Sixty with fixed hold time modus in 0.5–2, 2–5 mL, or 10–20 mL capped microwave vials. All reactions were monitored by thin-layer chromatography (TLC) on silica platted aluminum sheets (Silica gel 60 F254, E. Merck). Spots were detected by UV light (254 or 365 nm). Purification by flash column...
chromatography was performed using an automatic Biotage SP4 Flash + instrument. Prefabricated columns of two different cartridge sizes (surface area 500 m²/g, porosity 60 Å, particle size 40–63 μm) were used. The NMR spectra were measured with a JEOL JNM-ECP 400 or a Varian 400-MR spectrometer. ¹H and ¹³C NMR spectra were measured at 400 and 100 MHz, respectively. Chemical shifts are reported in ppm with the solvent residual peak as internal standard (CDCl₃, δH 7.26, δC 77.16; CD2OD, δH 3.31, δC 49.00; acetone-d₆, δH 2.05, δC 29.84; DMSO-d₆, δH 2.50, δC 39.52). All NMR experiments were measured at ambient temperature. Melting points were measured with a Mettler FP28 hot stage equipped with a FP80 temperature controller or Büchi Melting point B-545 and are uncorrected. Positive ion mass spectra (ESI-MS) were acquired with an LCQ quadrupole ion trap mass spectrometer (Finnigan LTQ) equipped with an electrospray ionization source or on a PerkinElmer API 150EX mass spectrometer. Combustion analyses for CHN were measured on a Thermo Quest CE Instruments EA 1110 CHNS-O elemental analyzer. High-resolution mass spectrometry (HRMS) analysis was performed on a Waters LCTq XL mass spectrometer with an Acquity UPLC BEH C18 (pH 10) or an Acquity UPLC CSH C18 (pH 3) column eluting with a gradient of 5–95% acetonitrile in water confirming ≥95% purity. Waters MassLynx 4.1 software was used for data analysis. Compounds 1, 2, and 20–23 have been synthesized according to procedures earlier reported by our group ¹², ¹³ and by Anknner et al. ¹⁴

**General Procedure for the Swern Oxidation to Obtain Aldehydes 4a−d, 4g**. The aldehyde was synthesized according to the general procedure from 3-(pyridine-2-yl)propan-1-al (1.1 equiv) in EtOH. The mixture was heated by microwave irradiation at 170 °C for 1–2 h (fixed hold time, normal absorption), and the solvent was removed in vacuo. The residue was dissolved in EtOAc and washed with 10% NaOH (aq), 1 M HCl (aq), water, and finally with brine. The organic phase was dried over MgSO₄ filtered, and concentrated under reduced pressure. Purification by flash column chromatography gave chroman-4-ones 6a−d. For the synthesis of 6a−c, the corresponding TBDMs-protected chroman-4-ones 5a−c were dissolved in MeOH (0.1 M). Selectfluor (0.2 mmol) was added, and the mixture was heated by microwave irradiation to 150 °C for 30 min. The mixture was concentrated and purified by flash column chromatography to give chroman-4-ones 6a−c.

8-Bromo-6-chloro-2-(3-hydroxypropyl)chroman-4-one (6a). The compound was synthesized according to the general procedure from 4a (crude, 974 mg), 3-bromo-5-chloro-2-hydroxyacetophenone (1.28 g, 5.13 mmol), and DIPA (1 mL, 7.1 mmol) to give 5a (2.00 g). An aliquot (460 mg, 0.86 mmol) was further reacted with Selectfluor (77 mg, 0.22 mmol). Flash column chromatography was performed using EtOAc/heptane (2:8 → 6:4) as eluent to afford 6a (280 mg, 78% over three steps) as a white solid; mp 88–89 °C. ¹H NMR (CDCl₃), δH 7.78 (d, J = 2.5 Hz, 1H), 7.68 (d, J = 2.5 Hz, 1H), 4.64−4.48 (m, 1H), 3.83−3.70 (m, 2H), 2.79−2.66 (m, 2H), 2.10−1.75 (m, 4H). ¹³C NMR (CDCl₃) δ 190.5, 156.6, 138.5, 127.1, 125.9, 122.4, 112.8, 79.0, 62.2, 42.6, 32.13, 28.3. Anal. (C₂₃H₁₃BrClO₂) C, H, N.

8-Bromo-6-chloro-2-(4-hydroxybutyl)chroman-4-one (6b). The compound was synthesized according to the general procedure from 4b (crude, 2.00 g). 3-bromo-5-chloro-2-hydroxyacetophenone (2.65 g, 10.6 mmol), and DIPA (1.95 mL, 13.8 mmol). The obtained chroman-4-one 5b (3.04 g) was directly reacted with Selectfluor (480 mg, 1.35 mmol). Flash column chromatography was performed using EtOAc/heptane (2:8 → 6:4) as eluent to afford 6b (1.78 g, 56% over three steps) as a white solid; mp 94−96 °C. ¹H NMR (CDCl₃), δ 7.80 (d, J = 2.6 Hz, 1H), 7.70 (d, J = 2.6 Hz, 1H), 4.57−4.48 (m, 1H), 3.71 (t, J = 5.9 Hz, 2H), 2.79−2.66 (m, 2H), 2.05−1.92 (m, 1H), 1.84−1.50 (m, 5H). ¹³C NMR (CDCl₃) δ 190.6, 156.7, 138.6, 127.1, 125.9, 122.5, 112.9, 79.0, 62.7, 42.5, 34.5, 32.3, 21.6. Anal. (C₂₅H₁₅BrClO₂) C, H, N.
8-Bromo-6-chloro-2-(2-methoxyethoxy)methylchroman-4-one (6c). The compound was synthesized according to the general procedure from 5b (197 mg, 0.44 mmol) in dry THF (2 mL), and the reaction mixture was stirred at room temperature for 17 h. The mixture was concentrated under reduced pressure, and the crude product was purified by flash chromatography using EtOAc/heptane (1:9) as eluent to afford 6d (420 mg, 67%). 8-Bromo-6-chloro-2-(2-(pyridin-3-yl)ethyl)chroman-4-one (6f). The compound was synthesized according to the general procedure from 4f (crude, 420 mg), 8-Bromo-6-chloro-2-(2-(pyridin-3-yl)ethyl)chroman-4-one (445 mg, 1.78 mmol), and DIPA (0.34 mL, 2.41 mmol). Flash chromatography was performed using EtOAc/heptane (20:80 → 55:45) as eluent to afford 6g (289 mg, 49% over two steps) as a yellow solid; mp 81–82 °C. 8-Bromo-6-chloro-2-chloro-2-oxo-2,3-dihydrobenzo[b][1,4]dioxin (6a). The compound was synthesized according to the general procedure from an aliquot of 4g (crude, 134 mg), 8-Bromo-6-chloro-2-chloro-2-oxo-2,3-dihydrobenzo[b][1,4]dioxin (247 mg, 0.99 mmol), and DIPA (0.15 mL, 1.06 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6a (200 mg, 29% over two steps) as an off-white solid; mp 121–122 °C. 8-Bromo-6-chloro-2-chloro-2-oxo-2,3-dihydrobenzo[b][1,4]dioxin (6b). The compound was synthesized according to the general procedure from 5b (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6b (633 mg, 62% as a white solid; mp 224–225 °C. Tetrahydrofuran-2,3-diol (6f). The compound was synthesized according to the general procedure from 5b (240 mg, 0.53 mmol), and DIPA (0.37 mL, 2.63 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6f (255 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6h). The compound was synthesized according to the general procedure from 5d (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6h (633 mg, 62% as a white solid; mp 224–225 °C. Tetrahydrofuran-2,3-diol (6i). The compound was synthesized according to the general procedure from 5e (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6i (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6j). The compound was synthesized according to the general procedure from 5f (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6j (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6k). The compound was synthesized according to the general procedure from 5g (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6k (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6l). The compound was synthesized according to the general procedure from 5h (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6l (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6m). The compound was synthesized according to the general procedure from 5i (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6m (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6n). The compound was synthesized according to the general procedure from 5j (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6n (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6o). The compound was synthesized according to the general procedure from 5k (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6o (633 mg, 69% as a white solid; mp 74–75 °C. Tetrahydrofuran-2,3-diol (6p). The compound was synthesized according to the general procedure from 5l (200 mg, 0.44 mmol). Flash chromatography was performed using EtOAc/heptane (3:7 → 100% EtOAc) as eluent to afford 6p (633 mg, 69% as a white solid; mp 74–75 °C.
Methyl 4-(8-Bromo-6-chloro-4-oxo chroman-2-yl)propanoate (9a). 3'-Bromo-5'-chloro-2'-hydroxyacetophenone (250 mg, 0.97 mmol) were added to a vial followed by EtOH (2 mL). The mixture was stirred for 45 min at room temperature. The reaction was quenched by the addition of 10% Na2SO4 solution in water, and the aqueous phase was extracted with EtOAc. The combined organic phases were dried over MgSO4, filtered, and concentrated under reduced pressure. Purification by flash chromatography using EtOAc/hexane (2:8) gave 9a (300 mg, 40%) as an off-white solid; mp 177 °C.

Flash chromatography was performed using EtOAc/heptane (3:7) to afford 10a (716 mg, 74% over two steps) as an off-white solid; mp 124–125 °C. 1H NMR (CDCl3) δ 7.81 (d, J = 2.5 Hz, 1H), 7.75 (d, J = 2.6 Hz, 1H), 4.65–4.50 (m, 1H), 3.72 (s, 3H), 2.89–2.53 (m, 4H), 2.30–2.01 (m, 2H). 13C NMR (CDCl3) δ 190.1, 173.2, 156.4, 138.6, 127.3, 126.0, 122.5, 112.9, 77.9, 52.0, 42.5, 29.9, 29.5. Anal. (C12H10BrClO4) C, H, N.

Methyl 4-(8-Bromo-6-chloro-4-oxo chroman-2-yl)butanoate (9b). 3'-Bromo-5'-chloro-2'-hydroxyacetophenone (242 mg, 0.97 mmol), 8b (139 mg, 1.07 mmol), and piperidine (0.01 mL, 0.97 mmol) were added to a microwave vial followed by EtOH (2 mL). The mixture was heated by microwave irradiation to 170 °C for 30 min. The solvent was removed under reduced pressure. Purification by flash chromatography using EtOAc/CH2Cl2 (3:97) to a vial gave 9b (250 mg, 2.15 mmol). 1H NMR (CDCl3) δ 7.84 (d, J = 2.6 Hz, 1H), 7.71 (d, J = 2.3 Hz, 1H), 4.65–4.50 (m, 1H), 3.72 (s, 3H), 2.89–2.53 (m, 4H), 2.30–2.01 (m, 2H). 13C NMR (CDCl3) δ 190.1, 173.2, 156.4, 138.6, 127.3, 126.0, 122.5, 112.9, 77.9, 52.0, 42.5, 29.9, 29.5. Anal. (C12H10BrClO4) C, H, N.

General Procedure for the Synthesis of Amides 11a–e. A 0.14 M solution of the appropriate carboxylic acid (1 equiv) in dry CH2Cl2 containing 5–10 vol % DMF was cooled to 0 °C under inert atmosphere. N,N'-Carbonyldiimidazole (1.5 equiv) was added, and the mixture was stirred for 30 min. The amine (3 equiv) was added, and the mixture was stirred at room temperature for 2–14 h. The mixture was diluted with CH2Cl2 and washed with 1 M HCl (aq) and brine, dried over MgSO4, filtered, and concentrated under reduced pressure. Purification by flash chromatography gave the amides 11a–e.

3-(8-Bromo-6-chloro-4-oxo chroman-2-yl)propanoic acid (10a). To a solution of 6a (378 mg, 1.18 mmol) in dry CH2Cl2 (15 mL) was added 3'-carbonyldiimidazole (60 mg, 0.37 mmol). Flash chromatography was performed using MeOH/CH2Cl2 (8:2) to afford 10a (66 mg, 22%) as an off-white solid; mp 135–136 °C. 1H NMR (CDCl3) δ 7.84 (d, J = 2.6 Hz, 1H), 7.76 (d, J = 2.6 Hz, 1H), 4.70–4.58 (m, 1H), 2.90–2.54 (m, 4H), 2.21–2.03 (m, 2H). 13C NMR (CDCl3) δ 191.8, 176.4, 157.9, 139.2, 127.8, 126.4, 123.8, 113.8, 80.3, 52.0, 43.1, 34.9, 34.3, 21.8. Anal. (C12H10BrClO4) C, H, N.

Flash chromatography was performed using MeOH/CH2Cl2 (8:2) to a vial gave 10b (74 mg, 24%) as a white solid; mp 128 °C. 1H NMR (CDCl3) δ 7.81 (d, J = 2.6 Hz, 1H), 7.75 (d, J = 2.6 Hz, 1H), 4.65–4.55 (m, 1H), 3.67 (s, 3H), 2.85–2.69 (m, 2H), 2.47 (t, J = 7.0 Hz, 2H), 2.07–1.73 (m, 4H). 13C NMR (CDCl3) δ 192.1, 175.5, 158.1, 139.1, 127.7, 126.4, 123.8, 113.8, 80.3, 52.0, 43.1, 34.9, 34.3, 21.8. Anal. (C12H10BrClO4) C, H, N.

Methyl 4-(8-Bromo-6-chloro-4-oxo chroman-2-yl)butanamide (11a). The title compound was synthesized according to the general procedure from 10a (99 mg, 0.30 mmol), methylamine hydrochloride (62 mg, 0.91 mmol), and N,N'-carbonyldiimidazole (73 mg, 1.52 mmol). Flash chromatography was performed using MeOH/CH2Cl2 (3:7) to afford 11a (70 mg, 68%) as a white solid; mp 178–180 °C. 1H NMR (CDCl3) δ 7.81 (d, J = 2.4 Hz, 1H), 7.70 (d, J = 2.5 Hz, 1H), 5.63 (br s, 1H), 4.61–4.51 (m, 1H), 2.86–2.66 (m, 5H), 2.51 (app t, 2H), 2.26–2.07 (m, 2H). 13C NMR (CDCl3) δ 190.1, 172.2, 156.3, 138.5, 127.3, 126.1, 122.6, 78.0, 42.5, 31.6, 30.4, 26.6. Anal. (C12H12BrClNO3) C, H, N.

4-(8-Bromo-6-chloro-4-oxo chroman-2-yl)-N-methylbutanamide (11b). The title compound was synthesized according to the general procedure from 10b (100 mg, 0.28 mmol), methyl amine hydrochloride (60 mg, 0.89 mmol), and N,N'-carbonyldiimidazole (72 mg, 0.44 mmol). Flash chromatography was performed using MeOH/CH2Cl2 (3:7) to afford 11b (96 mg, 93%) as a white solid; mp 136–139 °C. 1H NMR (CDCl3) δ 7.78 (d, J = 2.6 Hz, 1H), 7.69 (d, J = 2.6 Hz, 1H), 5.62 (s, 1H), 4.39–4.46 (m, 1H), 2.81 (d, J = 4.6 Hz, 3H), 2.76–2.06 (m, 2H), 2.24–1.75 (m, 4H). 13C NMR (CDCl3) δ 190.4, 173.0, 156.5, 138.5, 127.1, 125.9, 122.5, 112.7, 79.0, 42.5, 35.8, 34.1, 26.5, 21.4. Anal. Calcd for C13H15BrClNO3 C, H, N, 9888.
under reduced pressure.

A suspension of MgSO4 in MeCN (50 mL), and the reaction mixture was filtered, and concentrated under reduced pressure. 2H NMR (CDCl3) δ 7.82 (d, J = 2.5 Hz, 1H), 7.72 (d, J = 2.6 Hz, 1H), 4.60–4.50 (m, 1H), 4.46–4.31 (m, 2H), 3.04 (s, 3H), 2.80–2.69 (m, 2H), 2.26–1.84 (m, 4H). 13C NMR (CDCl3) δ 190.0, 156.3, 138.7, 127.6, 126.0, 122.5, 112.8, 78.4, 69.3, 42.6, 46.1, 37.7, 31.0, 25.4.

8-Bromo-chrom-4-one (12a). Morpholine (50 μL, 0.57 mmol) was added to a solution of 16 (90 mg, 0.24 mmol) in dry THF (2.5 mL). The mixture was heated by microwave irradiation at 100 °C for 40 min and 150 °C for 25 min. The mixture was concentrated under reduced pressure, and flash column chromatography was performed using MeOH/CH2Cl2 (5:95) followed by an acid–base extraction with 1 M HCl and NaOH (aq) to afford 17a (84 mg, 51%) as a yellow oil. 1H NMR (CDCl3) δ 7.78 (d, J = 2.6 Hz, 1H), 7.68 (d, J = 2.6 Hz, 1H), 4.61–4.49 (m, 1H), 3.72–3.66 (m, 6H), 2.79–2.64 (m, 2H), 2.49–2.35 (m, 6H), 2.10–2.04 (m, 2H), 1.97 (m, 1H), 1.75 (d, J = 2.5 Hz, 1H), 1.32 (t, J = 2.2 Hz, 3H), 0.98 (s, 9H). 13C NMR (CDCl3) δ 190.5, 156.8, 138.5, 127.0, 125.9, 122.5, 112.8, 77.0, 61.7, 58.4, 53.8, 42.6, 32.6, 22.0. Anal. (C7H8BrCINO) C, H, N.

8-Bromo-chrom-2-(3-morpholinopropyl)chrom-4-one (17a). Morpholine (50 μL, 0.57 mmol) was added to a solution of 16 (101 mg, 0.25 mmol) in dry THF (2.5 mL). The mixture was heated by microwave irradiation at 120 °C for 1 h and concentrated under reduced pressure. Flash column chromatography was performed using MeOH/CH2Cl2 (5:95) followed by an acid–base extraction with 1 M HCl and NaOH (aq) to afford 17a (38 mg, 39%) as a yellow oil. 1H NMR (CDCl3) δ 7.77 (d, J = 2.6 Hz, 1H), 7.68 (d, J = 2.6 Hz, 1H), 4.61–4.49 (m, 1H), 3.72–3.66 (m, 6H), 2.79–2.64 (m, 2H), 2.49–2.35 (m, 6H), 2.10–2.04 (m, 2H), 1.97 (m, 1H), 1.32 (t, J = 2.2 Hz, 3H), 0.98 (s, 9H). 13C NMR (CDCl3) δ 190.5, 156.7, 138.5, 127.0, 125.9, 122.5, 112.8, 77.0, 61.7, 58.4, 53.8, 42.6, 32.6, 22.0. Anal. (C7H8BrCINO) C, H, N.
Na₂CO₃ (aq) were added to the residue. The phases were separated, filtered, and the aqueous phase was extracted with EtOAc. The combined aqueous phase was extracted three times with EtOAc, and the organic phase was washed with MgSO₄ and concentrated under vacuum. Purification by flash chromatography using EtOAc:hexane (1:2) gave 25 (17 mg, 66%) as a beige solid; mp 106–108 °C. ¹H NMR (CDCl₃) δ 9.24 (br d, J = 10.3 Hz, 1H), 7.80 (d, J = 2.6 Hz, 1H), 7.61 (d, J = 9.5 Hz, 1H), 7.34–7.35 (m, 5H), 6.86–6.78 (m, 1H), 5.22 (br s, 1H). ¹³C NMR (CDCl₃) δ 180.9, 153.3, 147.5, 141.0, 136.6, 128.4, 126.6, 126.9, 126.2, 125.7, 125.3, 112.5, 102.8, 79.2, 37.6, 31.8. The compound is 97% pure according to HPLC analysis.

In Vitro Fluor de Lys Assay for SIRT1–3 Activities. The Fluor de Lys fluorescence assays were based on the method described in the BioMol product sheet (Enzo Life Sciences) using the BioMol KI177 substrate for SIRT1 and the KI179 substrate for SIRT2 and SIRT3. The determined Kᵅ values of SIRT1 for KI177 was 50 μM, and Kᵅ values of SIRT2 for KI179 was 198 μM. The IC₅₀ of KI179 was reported by BioMol to be 32 μM. The Kᵅ values of SIRT1, SIRT2, and SIRT3 for NAD⁺ were reported by BioMol to be 558 μM, 547 μM, and 2 mM, respectively.

Briefly, assays were carried out using the Fluor de Lys acetylated peptide substrate at a concentration corresponding to 0.7 Kᵅ and NAD⁺ (N6522, Sigma) at a concentration corresponding to 0.9 Kᵅ. The reactions were carried out using 50 μM Fluor de Lys HDAC substrate (KI104, Enzo) and 200 μM Fluor de Lys developer plus 1 μM Fluor de Lys HDAC substrate (KI104, Enzo) and 200 μM test compounds with HeLa cell nuclear extract (K410, Enzo) as a source of HDAC enzymatic activity. The reaction mixture was incubated for 1 h at 37 °C. Fluorescence readings were obtained using EnVision 2104 multilabel reader (PerkinElmer) with excitation wavelength 370 nm and emission 460 nm.

The IC₅₀ values were determined as three independent determinations with 8–10 different inhibitor concentrations in each determination. This gave altogether 27 data points that were included in the calculation of the best-fit value for nonlinear curve fitting with GraphPad Prism5 (GraphPad Software, Inc.).

Histone Deacetylase (HDAC) Activity Assay. The assay was done according to the instructions of the HDAC fluorometric assay/ drug discovery kit (AK500, Enzo). Briefly, the assay was carried out using 50 μM Fluor de Lys HDAC substrate (K104, Enzo) and 200 μM test compounds with HeLa cell nuclear extract (K410, Enzo) as a source of HDAC enzymatic activity. The reaction mixture was incubated for 1 h at 37 °C. After that, Fluor de Lys developer plus 1 μM Trichostatin A was added and incubation was continued for 15...
min at 25 °C. Fluorescence readings were obtained with EnVision 2104 multilabel reader (PerkinElmer) with excitation wavelength 370 nm and emission 460 nm. 

SIRTainty Sirtuin Activity Assay. The fluorometric SIRTainty class III HDAC assay (Millipore) employs nicotinamidase to measure nicotinamide generated upon the cleavage of NAD+ during sirtuin-mediated deacetylation of a substrate.59 The SIRT2 activity testing was performed according to the assay instructions in the presence and absence of NAD+. The results were read using Victor 1420 multilabel counter (Wallac) with excitation wavelength 405 nm and emission 460 nm and were reported as % of inhibition of the NAD+-dependent signal.

Cell Culture. Human A549 lung carcinoma cells and MCF-7 breast carcinoma cells (both from ATCC) were maintained in Dulbecco’s Modified Eagle Medium (DMEM) containing 10% fetal calf serum, 100 U/mL penicillin, and 100 μg/mL streptomycin (all from Gibco) at +37 °C in a humidified atmosphere of 5% CO2/95% air.

Cell Proliferation and Cell Cycle Analysis. For cell proliferation assays with sulforhodamine B, the cells were plated to 96-well plates (Nunc) 24 h before the start of the treatments (3000 cells/well). The cells were treated with vehicle (0.5% DMSO) or test compounds for 48 h (A549 cells) or 72 h (MCF-7 cells). Sulforhodamine B staining was performed as previously described.60 For cell cycle analysis with propidium iodide staining, the cells were plated to 6-well plates (Nunc) 6 h before the start of the treatments (0.6 × 106 cells/well). The cells were treated with vehicle (0.5% DMSO) or test compounds for 18 h. Propidium iodide staining was performed as previously described.61 FACSanto II flow cytometer with FACSdiva software (Becton Dickinson) was used to analyze cellular DNA content and cell cycle.

Western Blotting. The MCF-7 cells were plated to 12-well plates (Nunc) at a density of 105 cells/well, and the experiments were initiated after 24 h. The cells were treated with vehicle (0.5% DMSO) or test compounds as previously described.62 For the analysis of α-tubulin acetylation levels, the cells were lysed into M-PER mammalian protein extraction reagent (Thermo Fisher Scientific) followed by centrifugation (20 min, 16000g, +4 °C). After electrophoretic separation in SDS-PAGE gel, the proteins were transferred onto Hybond-ECL nitrocellulose transfer membrane (GE Healthcare) and were detected with mouse monoclonal acetylated α-tubulin antibody (T6793, Sigma) and total α-tubulin antibody (TS168, Sigma). The protein signals were visualized with peroxidase-conjugated sheep antinoice secondary antibody (ab97046, Abcam) and ECL Plus chemiluminescent substrate (GE Healthcare). The images were obtained by the use of digital imaging (ImageQuant, GE Healthcare).

Statistical Analyses. Statistical differences between groups were tested using one-way analysis of variance (ANOVA), followed by Tukey’s Multiple Comparison Test, with p < 0.05 considered as statistically significant. Data analysis was performed using GraphPad Prism version 5.03 for Windows (GraphPad Software).

ASSOCIATED CONTENT

S Supporting Information
Characterization data and elemental analysis or HRMS analyses for all tested compounds; complete list of SIRT1–3 activity assay results; list of calculated physicochemical properties of all tested compounds; description of the SIRT2 homology modeling procedure and validation; 1H NMR and 13C NMR spectra of all compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
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ABBREVIATION USED

Ac, acetyl; ADP, adenosine diphosphate; ADPβ, adenosine diphosphate ribose; ANOVA, analysis of variance; BSA, bovine serum albumin; DDQ, 2,3-dichloro-5,6-dicyano-p-benzoquinone; DIBAL–H, diisobutylaluminum hydride; DIPA, N,N-diisopropylamine; DMF, dimethylformamide; DMSO, dimethyl sulfoxide; DNA, deoxyribonucleic acid; ECL, enhanced chemiluminescence; ESI-MS, electrospray ionization mass spectrometry; FOX, Forkhead box protein; GST, glutathione-S-transferase; HDAC, histone deacetylase; HPLC, high-performance liquid chromatography; IC50, the half-maximal inhibitory concentration; KHMDS, potassium bis(trimethylsilyl)amide; LDA, lithium diisopropylamide; LDS, lithium dodecyl sulfate; MS, methanesulfonyl; MW, microwave; NAD+, nicotinamide adenine dinucleotide; NMR, nuclear magnetic resonance; PDB, Protein Data Bank; SAR, structure-activity relationship; SDS-PAGE, sodium dodecyl sulfate polyacrylamide gel electrophoresis; SEM, standard error of the mean; SIRT, silent information regulator type; TAA, tetra-N-butylammonium acetate; TB DMS, tert-butyl(dimethyl)silyl; TEMPO, (2,2,6,6-tetramethylpiperidin-1-yl)oxy; THF, tetrahydrofuran; TLC, thin-layer chromatography; TPAP, tetrapropylammonium peroxutenate; Ts, tosyl; p-TSA, p-toluenesulfonic acid; UV, ultraviolet

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(63) The docking was performed using the Glide docking tool as implemented in the Schrödinger software.


