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3-Hydroxypyrimidine-2,4-diones as an Inhibitor Scaffold of HIV Integrase

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Abstract

Integrase (IN) represents a clinically validated target for the development of antivirals against human immunodeficiency virus (HIV). Inhibitors with a novel structure core are essential for combating resistance associated with known IN inhibitors (INIs). We have previously disclosed a novel dual inhibitor scaffold of HIV IN and reverse transcriptase (RT). Here we report the complete structure-activity relationship (SAR), molecular modeling and resistance profile of this inhibitor type on IN inhibition. These studies support an antiviral mechanism of dual inhibition against both IN and RT and validate 3-hydroxypyrimidine-2,4-diones as an IN inhibitor scaffold.

Introduction

HIV infection and the establishment of proviral latency depend critically on the insertion of viral DNA into host genome.[1–3] This integration process comprises two distinct steps: 3′ processing (3′P) in which a sequence-specific endonucleolytic cleavage of the viral DNA generates a CA-OH at the 3′ end; and strand transfer (ST) where the processed viral DNA is inserted into the host genome through a transesterification reaction using the 3′ CA-OH as the nucleophile.[4] The virally encoded enzyme IN catalyzes both reactions; thus represents an important target for HIV chemotherapeutic intervention. IN as an antiviral target is rendered particular attractive by the lack of host cellular counterpart. On the other hand, IN uses the same active site (DD35E motif) for both steps where either a viral DNA (in 3′P) or a cellular DNA (in ST) serves as the endogenous substrate. Therefore, inhibitors of IN could also benefit from a potentially high genetic barrier to resistance development. In the past two decades, IN-targeted antiviral research has led to the identification of various inhibitor types, of which the most prominent scaffolds all feature a diketoacid (DKA) functionality or its heterocyclic bioisosteres.[5–9] These chemotypes can accommodate highly selective ST inhibition and have played an essential role in unraveling the pharmacophore requirements for IN binding.[10–15] Extensive research on these chemotypes culminated with a number of investigational drugs (Figure 1), including raltegravir (**1**)[16, 17], the first and only INI presently approved for clinical use; elvitegravir (**2**)[18], a promising candidate in phase III development; and S/GSK-1349572 (**3**)[19, 20], a second-generation IN inhibitor in phase IIb trials.[21] In the meantime, HIV integration also involves a cellular co-factor LEDGF/p75.[22–

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Supporting Information Available: Additional experimental details and NMR, MS, and HPLC data for **31, 34–41, 57–63 and 72–76**. This material is available free of charge via the Internet at http://pubs.acs.org.

[24] Targeting the protein-protein interaction between IN and LEDGF/p75 represents an emerging approach to HIV chemotherapeutic intervention.[25] Collectively inhibitors targeting IN can substantially enhance the current highly active anti-retroviral therapy (HAART), the standard chemotherapy for HIV/AIDS.[26] However, mutations conferring resistance to these inhibitors have been generated in cell culture and emerged in clinical studies[27–29], suggesting that INIs will be confronted with the same resistance issue that has plagued HIV/AIDS chemotherapy. Continued search for structurally novel INIs to combat resistance is therefore urgently needed. Previously we have reported that N-3 hydroxylation of pyrimidine-2,4-diones yielded inhibitors dually active against HIV reverse transcriptase (RT) and IN (**4**, figure 1).[30] Since this scaffold represents a novel chemotype for INIs, further SAR efforts on IN inhibition are warranted.

HIV IN is a 32-kDa protein encoded by viral pol gene consisting of three functional domains[31]: the N-terminal domain (NTD) with a conserved "HH-CC" zinc-binding motif; the catalytic core domain (CCD) containing the key D64-D116-E152 catalytic triad; and the C-terminal domain (CTD) important for DNA binding. Crystal structures of each single domain as well as double domains have been resolved[32–34], albeit without the binding of viral DNA substrate. Detailed understanding on HIV IN catalysis requires structural information on a DNA-bound full-length IN complex, or an intasome, which currently remains elusive due to major technical barriers[35] in obtaining stable HIV intasome. Recently disclosed crystal structures of a homologous prototype foamy virus (PFV) intasome[36, 37] have revealed the requisite catalytic molecular network comprising IN, viral and/or host DNA substrates and the inhibitor, allowing a largely improved understanding on the mechanism of catalysis and inhibition of retroviral IN. Homologous models[38, 39] constructed based on these PFV crystal structures have provided valuable details into HIV IN mechanism of action and formed the basis for structure-based INI design. Significantly these models corroborate the minimal pharmacophore embedded in major INIs: a chelating triad capable of binding two Mg^{2+} ions, and a hydrophobic benzyl moiety. Our novel IN inhibitors are constructed around a pyrimidine-2,4-dione ring, a pharmacophore core that has found wide applications in medicinal chemistry.[40–43] Central to our design is to introduce an OH group on the N-3 position which, along with the two flanking carbonyl groups, would yield a chelating triad of C(O)N(OH)C(O) that mimics a DKA functionality (Figure 2, chelating domain). On the other hand, the hydrophobic benzyl moiety can be easily installed via an N-1 alkylation, and the mono- or di-halogenation of this terminal benzyl group will allow us to explore the halogen effect IN inhibition (Figure 2, aromatic domain). Furthermore, to ensure that this benzyl group can fit in the hydrophobic cavity, its spatial placement over the chelating triad has to be optimized. This can be achieved through a linker of different length (Figure 2, linker domain). Finally, the overall hydrophobicity of the inhibitor could be modified by altering the C5 and C6 substituents (Figure 2, hydrophobic domain).

Results and Discussion

Chemistry

The chemical synthesis of aromatic and chelating domains starts with a known 5,6-disubstituted pyrimidine-2,4-dione **5**[44, 45] (Scheme 1). Subsequent selective N-1 alkylation of **5** via a bis-silylated pyrimidine intermediate with an *in situ* generated chloromethyl ether allows the incorporation of the aromatic domain with an ether linkage (**6**–**10**, Scheme 1). As previously reported [30], the key N-3 hydroxylation was achieved via a base-mediated meta-chloroperbenzoic acid (mCPBA) oxidation. To assess the significance of this hydroxyl group on IN inhibition, an N-3 amino analogue (**15**) as well as analogues with an N-3 methyl or methoxy group were also synthesized (**10** and **14**, Scheme 1).

The synthesis of the linker domain is described in Scheme 2. Analogues with an ether linkage were easily prepared through a selective N-1 alkylation with a chloromethyl ether (Scheme 2, B). The requisite alcohols (**19**–**21**) were synthesized from commercial carboxylic acids via a direct reduction with LAH. The construction of all-carbon tethers in the linker domain, however, proved much more challenging. The BSA-assisted selective N-1 alkylation of pyrimidine-2,4-diones generally involves a chloromethyl ether as the alkylating agent. Same reaction with benzyl bromide was effected only under forcing conditions (microwave, high temperature and long reaction time; see Scheme 2, C). Generic alkyl halides fail to undergo alkylation with the bis-silylated pyrimidine intermediate, and base-mediated direct alkylation normally leads to a mixture of region-isomers. As it turned out, the introduction of all-carbon chain into N-1 requires multiple protection and deprotection steps (Scheme 2, D). In this event, the N-1 position was first protected with an easily introduced ethoxymethyl group, which allowed the protection of N-3 position with an acetophenone group. The N-1 ether linkage was then cleaved under acidic condition to yield the N-3 protected intermediate **35**. Base-mediated direct alkylation led to the incorporation of the carbon tethers followed by a Mg mediated N-3 deprotection to yield key N-1 alkylated intermediates **39**–**41**. All N-1 alkylated pyrimidine-2,4-diones were then oxidized with mCPBA to produce desired N-3 hydroxylated compounds (Scheme 2).

The synthesis of hydrophobic domain with variable C-5 and C-6 substituents (Scheme 3, A) was achieved through a similar N-3 hydroxylation of N-1 alkylated intermediates (**45**–**50** and **57**–**63**). Compounds with a slightly different scaffold, the 5,6-benzopyrimidine-2,4-diones (**75**–**76**), were also prepared to probe the effect of a fused benzene ring on IN inhibition. These analogues were synthesized via a route depicted in Scheme 3, C.

SAR on IN Inhibition

All synthetic analogues were first tested against recombinant HIV-1 IN using a gel assay. Both 3′P and ST functions were evaluated. As clearly shown in Tables 1–3, our scaffold tends to selectively inhibit ST as none of the analogues demonstrated inhibitory activity against 3′P.

Aromatic and Chelating Domains—We have shown previously[30] that removing the phenyl ring at the end of the N-1 pendant resulted in a significant loss of inhibition against IN, and that without the OH group the N(3)H analogue is completely inactive against IN. These findings corroborate the pharmacophore hypothesis that HIV-1 IN inhibition requires minimally a chelating domain and an aromatic domain. In this study, additional analogues were synthesized to further study these two domains. As shown in Table 1 and Figure 3, halogen substitution of the N-1 benzyl seems to significantly benefit IN binding. A fluorination at the para position (inhibitor **4**) leads to a 6-fold improvement in IN inhibition over the unsubstituted compound **11**. Further improvement in activity was only marginal with a 3-chloro-2-fluoro substituted analogue **13**, whereas a 2,4-difluoro compound **12** showed slightly reduced inhibition when compared to **4** (Table 1). On the other hand, replacing the N-3 OH group with H, Me, OMe or even NH_2 yielded compounds completely devoid of inhibitory activity against IN (**9**–**10** and **14**–**15**, Table 1), confirming the critical requirement of the N-3 OH for chelating Mg^{2+}. The lack of potency with the amino analogue **15** also reflects an inferior chelating ability of NH_2 for Mg^{2+} when compared to OH.[30]

The linker domain—Having established the chelating triad and the N-1 benzyl group as the two major structural determinants of our novel INI scaffold, our SAR efforts were then centered around the linker domain as it dictates the angle and distance between the chelator and benzyl group. Toward this end, we have designed linkers of different nature and length.

Compounds **4** and **28**–**30** all have an ether linkage with incremental methylene groups (Table 2). Interestingly, these analogues all exhibited inhibitory activity in ST assay at low micromolar range, and demonstrated a discernible binding dependence on the length of the linker. As shown in Table 2, the 4-atom linker $(CH_2)_2OCH_2$ (inhibitor **28**) conferred the highest inhibition within this series, and a reduced inhibition was achieved with compounds having a shorter (**4**) or longer linker (**29**–**30**). A similar albeit more sensitive trend was observed with compounds having an all carbon N-1 linker. In this case, short linkages, such as CH_2 (**32**) and $(CH_2)_2$ (**42**), appeared to pose severe binding difficulties while the 3- and 4-atom linkers $(CH_2)_3$ (**43**) and $(CH_2)_4$ (**44**) conferred a drastically improved inhibition against ST (Table 2). These findings strongly imply that the optimal IN inhibition entails a linker of 3–4 atoms. The nature of the linker (ether linkage vs all-carbon linkage) was also found to substantially impact IN inhibition as inhibitors **43** and **44** demonstrated significantly better inhibition than compound **28**. Detailed docking studies on the inhibitor binding may provide a molecular basis for this observation.

The hydrophobic domain—Synthetic analogues in these domains vary mainly in the size of the C-5 alkyl group (iPr, Et and Me) and fluorine substitution on the C-6 benzyl. These changes impact most likely the steric hindrance and the overall hydrophobicity of these inhibitors. Interestingly, a C-5 ethyl group was found to confer significantly better inhibition than isopropyl group (**53** vs **11**, Table 3), indicating that less steric hindrance at C-5 could benefit IN binding. However, a reversed effect was observed in compounds with an N-1 linker of CH_2, wherein a C-5 ethyl substitution (**67**) caused a complete loss of inhibition when compared to a C-5 isopropyl substitution (**66**). On the other hand, swapping C5 and C6 substituents of inhibitor **53** seems to harm IN binding (**55** vs **53**) as the IC_{50} value increased by 4-fold. Notably, a para-fluoro substitution at the C-6 benzyl clearly favors IN inhibition (**53** vs **11**, **56** vs **55**). With a more dramatic change, a C-5 and C-6 fused benzene ring was found to render compounds **75**–**76** completely inactive against IN inhibition (Table 3). These findings indicate that the hydrophobic domain affects IN binding in a less comprehensible way and changes in this domain impact the activity most likely in concert with the linker domain.

Modeling

The common mode of inhibitory binding was explored through molecular docking using a homologous HIV IN model[38] constructed based on the crystal structure of prototype foamy virus (PFV) IN.[36] Significantly, the new inhibitor **43** fits perfectly into the IN binding site through two major binding domains also featured in raltegravir (**1**): the chelation of two Mg^{2+} ions, and the placement of the 4-F-benzyl group into the protein-DNA interfacial hydrophobic pocket (Figure 4). The high degree of similarity shown between the binding of **1** and **43** confirms that our new molecular scaffold can effectively engage with HIV IN. Interestingly, while residue Y143 contributes siginificantly to binding of **1** through a π-stacking interaction (Figure 4, A), the same interaction was not observed with our inhibitor **43** (Figure 4, B), suggesting that our inhibitor could be less susceptible to resistance associated with Y143 mutation. It is also noteworthy that the linker domain is situated right in the hydrophobic cleft between residue P145 and viral DNA nucleobases. Therefore, an ether linkage may provide a less favorable hydrophobic interaction than an all-carbon linker, thus the observed reduced inhibition with the ether linkage (Table 2, **43** Vs **28**).

Further validation was achieved by correlating the SAR of docked inhibitors **4**, **11**, **28**, **29**, **30**, **32**, **42**, **43**, **44**, **66** as shown in Figure 5. The outstanding correlation observed between these two sets of IC_{50} data (exp. vs calc., correlation coefficiency = 0.82) supports our docking model with a common mode of binding as a valid platform for HIV IN inhibitor design.

Antiviral Assay

To evaluate the antiviral activity of newly synthesized INIs, all compounds with an IC_{50} of 10 μM or lower from IN ST assay were tested against HIV-1IIIB in CEM-SS cells using an assay based on viral cytopathic effect (CPE). In this assay, the reduction of CPE was used to indicate the antiviral activity of a compound. All selected compounds were first screened under a single concentration (10 μM). Inhibitors with excellent CPE reduction and cell viability from this screening assay were further tested in a dose response fashion, from which the EC_{50} and CC_{50} were determined. Table 4 summarizes the antiviral testing results.

Remarkably, compounds **43** and **44**, the two most potent INIs from IN ST assay with submicromolar IC_{50}s, have shown only marginal activity against HIV-1 at 10 μM (Table 4). This finding strongly suggests that despite their ability to confer exceptional IN inhibition in biochemical assays, all-carbon linkers lack the proper physicochemical properties for the compounds to reach their target in cell culture. By contrast, with the exception of compounds having a para-fluorine at the C-6 benzyl group (**49**–**50**, Table 4), INIs with an ether linkage of CH_2OCH_2 (**4**, **11**–**13** and **51**) showed antiviral activity at the low micromolar to low nanomolar range without appreciable cytotoxicity (Table 4). Longer ether linkages that produced excellent anti-IN activity for compounds **28**–**30** did not generate similar activity in the antiviral assay, further demonstrating that additional CH_2s in the linker domain hinder antiviral activity.

Resistance

To establish the resistance profile of our inhibitors, we first tested two representative inhibitors **4** and **13** against HIV IN mutants. In this study, major mutants associated with raltegravir resistance[23, 24], namely a G140S/Q148H double mutant and two single mutants Y143R and N155H were employed. The results are summarized in Table 5. Notably the G140S/Q148H double mutant which causes high resistance to raltegravir (**1**) yielded a much lower fold resistance to **4** and **13**, whereas the two single mutants confer comparable resistance to **4**, **13** and **1**, suggesting a potentially common binding mode for these inhibitors.

Based on these biochemical data, inhibitors **4** and **13** were further evaluated in cell culture against raltegravir-resistant HIV strains. Unlike the initial antiviral assay wherein HIV-1 IIIB was used in CEM-SS cells, the resistance studies were carried out with NL4-3 based viral strains in MT-4 cells. Selected strains contain major mutations corresponding to the IN mutants (Table 6 Vs Table 5). As shown in Table 6, all three viral strains show a high level resistance to raltegravir (**1**). Interestingly, although likely within experimental variations, the small fold-resistances observed with inhibitor **4** (Table 6) correlate closely with resistance observed with IN mutants in biochemical assays (Table 5). The testing of inhibitor **13** was complicated by its toxicity observed in MT-4 cells. Notably the same compound did not show toxicity in CEM-SS cells (TC_{50} > 100 μM, Table 4). On the other hand, antiviral assay with two HIV-1_{NL4-3} strains containing major mutations associated with NNRTI resistance, K103N or Y181C, revealed a fold-resistance of 16 and 48, respectively, to inhibitor **4**.[46] These results suggest that the overall antiviral activity of **4** could reflect a concerted yet not necessarily balanced inhibition to both RT and IN.

In summary, through complete SAR and docking studies we have demonstrated that the N-3 OH group and the 4-F-benzyl moiety on the N-1 side chain are the key structural determinants for IN inhibition, and that the linker domain sits in a hydrophobic cleft between DNA nucleobases and P145. Therefore, both the nature and the length of the linker greatly impact IN binding, with the optimal IN inhibition entailing a 3–4 atom all-carbon linkage. However, studies in cell culture revealed that inhibitors with an all-carbon linker

generally lack antiviral activity, presumably due to unfavored physicochemical properties. Resistance studies with raltegravir-resistant IN mutants as well as HIV-1_{NL4-3} viral strains demonstrated low level resistances toward inhibitors **13** and **4**, likely due to their anti-RT activity. In the end, compounds (**4**, **11** and **13**) featuring a CH_2OCH_2 linker demonstrate low micromolar IN inhibition and nanomolar anti-HIV activity, and are suitable for further development.

Experimental

Chemistry

General Procedures—All commercial chemicals were used as supplied unless otherwise indicated. Dry solvents (THF, Et_2O, CH_2Cl_2 and DMF) were dispensed under argon from an anhydrous solvent system with two packed columns of neutral alumina or molecular sieves. Flash chromatography was performed on a Teledyne Combiflash RF-200 with RediSep columns (silica) and indicated mobile phase. All reactions were performed under inert atmosphere of ultra-pure argon with oven-dried glassware. ^1H and ^{13}C NMR spectra were recorded on a Varian 600 MHz spectrometer. Mass data were acquired on an Agilent TOF II TOS/MS spectrometer capable of ESI and APCI ion sources. Analysis of sample purity was performed on a Varian Prepstar SD-1 HPLC system with a Varian Microsorb-MW 100-5 C18 column (250mm × 4.6 mm): solvent A = H_2O, solvent B = MeCN; flow rate = 1.0 mL/min; Method: linear 30–95% (B) over 25 min. All tested compounds have a purity ≥ 96%.

6-Benzyl-1-(benzyloxymethyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (6).[44]—To a suspension of paraformaldehyde (144 mg, 4.80 mmol) in TMSCl (2.0 mL), was added benzyl alcohol (518 mg, 4.80 mmol) at room temperature. The reaction mixture was stirred until a clear solution was formed. The solution was concentrated under reduced pressure to give benzyl chloromethyl ether as oil, which was taken to the next step without further purification. To a suspension of pyrimidine **5** (976 mg 4.00 mmol) in 16 mL of anhydrous DCM was added BSA (2.16 mL, 8.80 mmol) at room temperature. The resulting mixture was stirred until a clear solution was achieved. The freshly prepared benzyl chloromethy ether was added to this solution followed by the addition of a catalytic amount of TBAI. The reaction mixture was kept overnight and then quenched by adding a saturated aqueous solution of $NaHCO_3$. The aqueous phase was extracted with CH_2Cl_2 (20 mL × 3). The combined organic extracts were dried over Na_2SO_4 and concentrated under reduced pressure. The resultant residue was subjected to combiflash (Hex/EtOAc, 2:1) to afford compound **6** (1.25 g, 86 %) as a white solid. ^1H NMR (600 MHz, $CDCl_3$) δ 7.28 (m, 6H), 7.20 (m, 2H), 7.00 (d, *J* = 7.8 Hz, 2H), 5.14 (s, 2H), 4.59 (s, 2H), 4.10 (s, 2H), 2.79 (septet, *J* = 6.6 Hz, 1H), 1.21 (d, *J* = 6.6 Hz, 6H); MS (ESI+) m/z: 365.17 (M+1).

6-Benzyl-1-((2,4-difluorobenzyloxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (7)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 88 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 9.32 (s, 1H), 7.34 (m, 3H), 7.26 (t, *J* = 7.8 Hz, 1H), 7.07 (d, *J* = 7.8 Hz, 2H), 6.86 (t, *J* = 9.0 Hz, 1H), 6.81 (d, *J* = 9.0 Hz, 1H), 5.20 (s, 2H), 4.64 (s, 2H), 4.16 (s, 2H), 2.87 (m, 1H), 1.28 (d, *J* = 6.6 Hz, 6H); MS (ESI−) m/z: 399.42 (M-1).

6-Benzyl-1-((3-chloro-2-fluorobenzyloxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (8)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 90 %; ^{1} HNMR (600 MHz, $CDCl_3$) δ 8.96 (b, 1H), 7.36 (m, 3H), 7.33 (t, *J* = 7.8 Hz, 2H), 7.10 (m, 3H), 5.21 (s, 2H), 4.69 (s, 2H), 4.16 (s, 2H), 2.87 (m, 1H), 1.28 (d, *J* = 6.6 Hz, 6H); MS (ESI−) m/z: 415.87 (M-1).

6-Benzyl-1-((4-fluorobenzyloxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (9)—This compound was prepared as a white solid following the procedure described for the preparation of **6.** Yield: 89 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 8.97 (b, 1H), 7.34 (t, *J* = 7.2 Hz, 2H), 7.30 (m, 3H), 7.07 (d, *J* = 7.8 Hz, 2H), 7.03 (m, 2H), 5.20 (s, 2H), 4.61 (s, 2H), 4.16 (s, 2H), 2.88 (septet, *J* = 7.2 Hz, 1H), 1.28 (d, *J* = 7.2 Hz, 6H); MS (ESI+) m/z: 383.18 (M+1).

6-Benzyl-1-((4-fluorophenethoxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (25)—This compound was prepared as a white solid following the procedure described for the preparation of **6.** Yield: 89 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 8.89 (b, 1H), 7.27 (t, *J* = 7.2 Hz, 2H), 7.20 (m, 1H), 7.08(m, 2H), 6.99 (d, *J* = 7.8 Hz, 2H), 6.91 (t, *J* = 8.4 Hz, 2H), 5.04 (s, 2H), 3.94 (s, 2H), 3.71 (t, *J* = 6.6 Hz, 2H), 2.74 (m, 3H), 1.20 (d, *J* = 6.6 Hz, 6H); MS (ESI−) m/z: 395.45 (M-1).

6-Benzyl-1-((3-(4-fluorophenyl)propoxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (26)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 83 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 8.97 (b, 1H), 7.29 (t, *J* = 7.8 Hz, 2H), 7.21 (t, *J* = 7.8 Hz, 1H), 7.05 (m, 4H), 6.89 (t, *J* = 9.0 Hz, 2H), 5.05 (s, 2H), 4.11 (s, 2H), 3.50 (t, *J* = 6.0 Hz, 2H), 2.87 (septet, *J* = 7.2 Hz, 1H), 2.56 (t, *J* = 7.8 Hz, 2H), 1.78 (m, 2H), 1.23 (d, *J* = 6.6 Hz, 6H); MS (ESI−) m/z: 409 (M-1).

6-Benzyl-1-((4-(4-fluorophenyl)butoxy)methyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (27)—This compound was prepared as a white solid following the procedure described for the preparation of **6.** Yield: 84 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 10.01 (b, 1H), 7.34 (t, *J* = 7.8 Hz, 2H), 7.26 (t, *J* = 7.2 Hz, 1H), 7.10 (m, 4H), 6.94 (d, *J* = 9.0 Hz, 2H), 5.23 (s, 2H), 4.16 (s, 2H), 3.58 (t, *J* = 6.6 Hz, 2H), 2.86 (septet, *J* = 7.2 Hz, 1H), 2.58 (t, *J* = 7.2 Hz, 2H), 1.63 (m, 2H), 1.56 (m, 2H), 1.27 (d, *J* = 7.2 Hz, 6H); MS (ESI−) m/z: 423.51 (M-1).

6-Benzyl-1-(ethoxymethyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (33)—This compound was prepared as a white solid following the procedure described for the preparation of **6.** Yield: 89 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 8.68 (b, 1H), 7.29 (t, *J* = 7.8 Hz, 2 H), 7.22 (m, 2H), 7.06 (d, *J* = 7.8 Hz, 1H), 5.05 (s, 2H), 4.11 (s, 2H), 3.56 (q, *J* = 7.2 Hz, 2H), 2.81 (septet, *J* = 7.2 Hz, 1H), 1.22 (d, *J* = 6.6 Hz, 6H), 1.11 (t, *J* = 7.2 Hz, 3H); MS (ESI−) m/z: 301.37 (M-1).

1-(Benzyloxymethyl)-5-methylpyrimidine-2,4(1H,3H)-dione (48)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 82 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 9.21 (b, 1H), 7.34 (m, 5H), 7.10 (s, 1H), 5.21 (s, 2H), 4.66 (s, 2H), 4.62 (s, 2H), 1.91 (s, 3H); MS (ESI−) m/z: 245.10 (M-1).

5-Benzyl-1-(benzyloxymethyl)-6-ethylpyrimidine-2,4(1H,3H)-dione (49)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 78 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 9.64 (s, 1H), 7.31 (m, 4H), 7.24 (m, 3H), 6.99 (m, 3H), 5.43 (s, 2H), 4.67 (s, 2H), 4.08 (s, 2H), 2.73 (q, *J* = 6.6 Hz, 2H), 1.06 (t, *J* = 6.6 Hz, 3H); MS (ESI−) m/z: 349.62 (M-1).

5-Benzyl-6-ethyl-1-((4-fluorobenzyloxy)methyl)pyrimidine-2,4(1H,3H)-dione (50)—This compound was prepared as a white solid following the procedure described for the preparation of **6**. Yield: 80 %; ^{1} HNMR (600 MHz, $CDCl_3$) δ 9.51 (s, 1H), 7.29 (t, *J* = 7.2 Hz, 4H), 7.20 (d, *J* = 6.6 Hz, 2H), 7.00 (t, *J* = 6.6 Hz, 2H), 5.41 (s, 2H), 4.62 (s, 2H),

4.08 (s, 2H), 2.72 (q, *J* = 6.6 Hz, 2H), 1.07 (t, *J* = 6.6 Hz, 3H); MS (ESI−) m/z: 367.15 (M-1).

6-Benzyl-1-((4-fluorobenzyloxy)methyl)-5-isopropyl-3-methylpyrimidine-2,4(1H,3H)-dione (10)—A mixture of compound **9** (60 mg, 0.16 mmol), methyl iodide (27 mg, 0.19 mmol) and Cs_2CO_3 (61 mg, 0.19 mmol) in 2 mL of THF was stirred under 40 °C for 3 h, and then allowed to cool to room temperature. The reaction mixture was quenched by adding 5 mL of H_2O and extracted with EtOAc (10 mL × 3). The combined organic phases were dried over Na_2SO_4, and then concentrated under reduced pressure. The resultant residue was purified with combiflash to give compound **10** (40 mg, 63%) as clean oil: ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.25 (t, *J* = 7.8 Hz, 2H), 7.21 (m, 3H), 6.99 (d, *J* = 7.2 Hz, 2H), 6.95 (t, *J* = 8.4 Hz, 2H), 5.16 (s, 2H), 4.53 (s, 2H), 4.09 (s, 2H), 3.28 (s, 3H), 2.87 (septet, *J* = 7.2 Hz, 1H), 1.22 (d, *J* = 7.2 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 163.2, 161.8, 161.5, 152.6, 146.0, 135.4, 133.2 (d, *J* = 3.3 Hz), 129.6 (d, *J* = 7.8 Hz), 129.2, 127.3 (d, *J* = 7.4 Hz), 118.9, 115.4 (d, *J* = 21.2 Hz), 73.7, 71.0, 33.4, 28.2, 27.9, 20.4; MS (ESI−) m/z: 395.45 (M-1).

6-Benzyl-1-((4-fluorobenzyloxy)methyl)-5-isopropyl-3-methoxypyrimidine-2,4(1H,3H)-dione (14)—This compound was prepared following the procedure described for the preparation of **10**. Yield: 53 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.27 (t, *J* = 8.4 Hz, 2H), 7.24 (m, 3H), 6.99 (d, *J* = 7.2 Hz, 2H), 6.96 (t, *J* = 8.4 Hz, 2H), 5.14 (s, 2H), 4.55 (s, 2H), 4.08 (s, 2H), 3.94 (s, 3H), 2.85 (septet, *J* = 7.2 Hz, 1H), 1.22 (d, *J* = 7.2 Hz, 6H); MS (ESI−) m/z: 411.45 (M-1).

3-Amino-6-benzyl-1-(benzyloxymethyl)-5-isopropylpyrimidine-2,4(1H,3H)-dione (15).[30]—To a solution of **6** (60 mg, 0.16 mmol) in l.0 mL of THF was added NaH (31 mg, 0.82 mmol) at 0 °C. This reaction mixture was allowed to warm to room temperature over 1h., and then cooled to 0 °C followed by the addition of O-(Mesitylsulfonyl)hydroxylamine[47] (MSH, 66 mg, 0.32 mmol). After stirring for 0.5 h, this reaction mixture was stirred at rt overnight. The reaction was quenched by adding 10 mL of H_2O; the aqueous phase was then extracted with ethyl acetate (10 mL × 3). The combined organic extracts were dried over Na_2SO_4 and concentrated under reduced pressure. The resultant residue was subjected to combiflash (Hex/EtOAc, 1:1) to give compound **15** (22 mg, 54 % based on consumed start material) as a white solid: ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.33-7.26 (m, 8H), 7.04-7.03 (d, *J* = 7.2 Hz, 2H), 5.24 (s, 2H), 4.66 (s, 2H), 4.19 (s, 2H), 2.90 (septet, *J* = 7.2 Hz, 1H), 1.29 (d, *J* = 6.6 Hz, 6H); HRMS (ESI−) calcd. for $C_{22}H_{25}N_3O_3$ $[M-H]^-$ 380.1969, found 380.1976 (E = −1.9 ppm).

6-Benzyl-1-((4-fluorobenzyloxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (4).[47]—To a solution of **9** (100 mg, 0.26 mmol) in 6 mL of THF was added NaH (31 mg, 1.30 mmol) at 0 °C. This reaction mixture was allowed to warm to room temperature over 1 h., and then cooled to 0 °C followed by the addition of m-CPBA (135 mg, 0.79 mmol). This reaction mixture was allowed to warm to room temperature and stirred overnight. After the reaction was quenched by adding 10 mL of H_2O, the aqueous phase was acidified with 1N HCl to pH = 7, and then extracted with ethyl acetate (10 mL × 3). The combined organic extracts were dried over Na_2SO_4 and concentrated under reduced pressure. The resultant residue was subjected to combiflash (Hex/EtOAc, 1:1) to give compound **4** (38 mg, 72 % based on consumed start material) as a white solid. ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.33-7.26 (m, 5H), 7.04-6.99 (m, 4H), 5.03 (s, 2H), 4.64 (s, 2H), 4.19 (s, 2H), 2.90 (septet, *J* = 7.2 Hz, 1H), 1.29 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 163.3, 162.4, 161.6, 152.1, 148.3, 135.2, 133.1(d, *J* = 3.3 Hz), 129.7 (d, *J* = 7.8 Hz), 129.2, 127.2(d, *J* = 6.8 Hz), 119.9, 115.4 (dd, *J* = 21.2 Hz), 72.8, 70.9,

33.5, 28.2, 20.4; HRMS (ESI−) calcd. for $C_{22}H_{23}FN_2O_4$ $[M-H]^-$ 399.1715, found 399.1705 (E = 2.4 ppm).

6-Benzyl-1-(benzyloxymethyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (11)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 53 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.32-7.30 (m, 7H), 7.02 (*J* = 7.2 Hz, 2H), 5.30 (s, 2H), 4.67 (s, 2H), 4.19 (s, 2H), 2.90 (septet, *J* = 7.2 Hz, 1H), 1.28 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 162.2, 151.9, 148.4, 137.3, 135.3, 129.1, 128.5, 128.0, 127.8, 127.3, 127.2, 119.8, 73.0, 71.8, 33.5, 28.2, 20.4; HRMS (ESI−) calcd. for $C_{22}H_{24}N_2O_4$ $[M-H]^-$ 381.1809, found 381.1803 (E = 1.5 ppm).

6-Benzyl-1-((2,4-difluorobenzyloxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (12)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 73 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.18 (m, 1H). 7.20 (m, 2H), 7.14 (t, *J* = 7.2 Hz, 1H), 6.97 (d, *J* = 7.8 Hz, 2H), 6.73 (td, *J* = 1.8, 9.6 Hz, 1H), 6.67 (td, *J* = 1.8, 9.6 Hz, 1H), 5.13 (s, 2H), 4.55 (s, 2H), 4.04 (s, 2H), 2.75 (m, 1H), 1.13 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150, $CDCl_3$) δ 163.8 (d, *J* = 11.7 Hz), 162.1(dd, *J* = 7.8, 19.5 Hz), 160.4 (d, *J* = 11.7 Hz), 148.3, 135.2, 131.5 (d, *J* = 7.8 Hz), 129.2, 127.2, 120.4 (d, *J* = 15.6 Hz), 120.0, 111.2 (dd, *J* = 3.9, 21.2 Hz), 104.1 (t, *J* = 25.2 Hz), 72.7, 64.9, 33.4, 28.3, 20.3; HRMS (ESI−) calcd. for $C_{22}H_{22}F_2N_2O_4$$[M-H]^-$ 415.1475, found 415.1473 (E = 0.45 ppm).

6-Benzyl-1-((3-chloro-2-fluorobenzyloxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (13)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 85 %; ^{1}HNMR (600 MHz, CD_3OD) δ 7.32 (t, *J* = 6.6 Hz, 1H), 7.23 (m, 3H), 7.18 (t, *J* = 7.2 Hz, 1H), 7.05 (t, *J* = 7.8 Hz, 1H), 7.00 (d, *J* = 7.8 Hz, 2H), 5.29 (s, 2H), 4.67 (s, 2H), 4.11 (s, 2H), 2.87 (m, 1H), 1.22 (d, *J* = 7.2 Hz, 6H); ^{13}C NMR (150, $CDCl_3$) 163.7 (d, *J* = 11.7 Hz), 162.1 (t, *J* = 11.7 Hz), 160.4 (t, *J* = 11.7 Hz), 159.7, 144.2, 135.5, 131.8 (d, *J* = 11.7 Hz), 129.1, 127.3(t, *J* = 16.2 Hz), 120.5 (d, *J* = 11.1 Hz), 118.2, 116.6, 111.1 (dd, *J* = 3.5, 21.3 Hz), 103.9 (t, *J* = 25.1 Hz), 72.9, 65.5, 33.4, 28.3, 20.4; HRMS (ESI+) calcd. for $C_{22}H_{22}ClFN_2O_4$ $[M-H]^-$ 431.1179, found 431.1181 (E = −0.83 ppm).

6-Benzyl-1-((4-fluorophenethoxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (28)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 66 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.34 (t, *J* = 7.2 Hz, 2H), 7.29 (d, *J* = 7.2 Hz, 1H), 7.14 (m, 2H), 7.03 (d, *J* = 7.8 Hz, 2H), 6.97 (t, *J* = 8.4 Hz, 2H), 5.19 (s, 2H), 4.04 (s, 2H), 3.82 (t, *J* = 6.6 Hz, 2H), 2.88 (septet, *J* = 7.2 Hz, 1H), 2.81 (t, *J* = 6.6 Hz, 2H), 1.28 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 162.5 (d, *J* = 16.2 Hz), 160.7, 155.5, 152.1, 148.4, 135.4, 134.2 (d, *J* = 2.9 Hz), 130.3 (d, *J* = 7.8 Hz), 129.2, 127.2, 119.8, 115.2 (d, *J* = 21.2 Hz), 72.9, 70.0, 35.1, 33.3, 28.2, 20.4; HRMS (ESI+) calcd. for $C_{23}H_{25}FN_2O_4$ $[M+H]^+$ 413.1871, found 413.1868 (E = 0.76 ppm).

6-Benzyl-1-((3-(4-fluorophenyl)propoxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (29)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 71 %; ^{1} HNMR (600 MHz, $CDCl_3$) δ 7.33 (m, 2H), 7.26 (m, 1H), 7.07 (m, 2H), 7.01 (m, 2H), 6.95 (m, 2H), 5.19 (s, 2H), 4.18 (s, 2H), 3.58 (m, 2H), 2.89 (septet, *J* = 7.2 Hz, 1H), 2.60 (m, 2H), 1.82 (m, 2H), 1.29 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 162.9, 162.1, 160.5, 152.4, 148.5, 137.2 (d, *J* = 3.3 Hz), 135.4, 129.7 (d, *J* = 7.8 Hz), 129.2, 127.3 (d, *J* = 7.8 Hz), 119.9, 115.2

(d, *J* = 20.6 Hz), 73.0, 68.4, 33.5, 31.3, 31.1, 28.2, 20.4; HRMS (ESI+) calcd. for $C_{24}H_{27}FN_2O_4$ $[M+H]^+$ 427.2028, found 427.2026 (E = 0.38 ppm).

6-Benzyl-1-((4-(4-fluorophenyl)butoxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (30)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 64 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.34 (t, *J* = 7.2 Hz, 2H), 7.28 (d, *J* = 7.2 Hz, 1H), 7.11 (dd, *J* = 1.8, 7.8 Hz, 2H), 7.07 (d, *J* = 7.8 Hz, 2H), 6.96 (t, *J* = 8.4 Hz, 2H), 5.21 (s, 2H), 4.19 (s, 2H), 3.60 (t, *J* = 6.0 Hz, 2H), 2.91 (septet, *J* = 7.2 Hz, 1H), 2.58 (t, *J* = 7.2 Hz, 2H), 1.63 (m, 2H), 1.58 (m, 2H), 1.29 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150, $CDCl_3$) δ 162.7, 162.0, 160.4, 152.2, 148.5, 137.8 (d, *J* = 3.3 Hz), 135.4, 129.7 (d, *J* = 7.8 Hz), 129.2, 127.3 (d, *J* = 7.8 Hz), 119.8, 115.0 (d, *J* = 20.7 Hz), 73.1, 69.3, 34.7, 33.4, 29.2, 28.9, 28.1, 20.3; HRMS (ESI+) calcd. for $C_{25}H_{29}FN_2O_4$ $[M+H]^+$ 441.2184, found 441.2164 (E = 4.6 ppm).

6-Benzyl-1-(4-fluorobenzyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (32)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 72 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.30 (t, *J* = 7.2 Hz, 2H), 7.05-7.03 (m, 3H), 6.98 (d, *J* = 7.2 Hz, 2H), 6.94 (m, 2H), 4.88 (s, 2H), 3.83 (s, 2H), 2.81 (septet, *J* = 7.2 Hz, 1H), 1.22 (d, *J* = 6.6 Hz, 6H,); HRMS (ESI+) calcd. for $C_{21}H_{21}FN_2O_3$ $[M+H]^+$ 369.1609, found 369.1608 (E = 0.26 ppm).

6-Benzyl-1-(4-fluorophenethyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (42)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 62 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.26–7.24 (m, 2H), 7.21 (m, 1H), 6.97(m, 2H), 6.89-6.88 (m, 2H), 6.85-6.84 (m, 2H), 3.79 (s, 2H), 3.73 (t, *J* = 7.8 Hz, 2H), 2.82 (septet, *J* = 7.2 Hz, 1H), 2.68 (t, *J* = 7.8 Hz, 2H), 1.29 (d, *J* = 6.6 Hz, 6H); HRMS (ESI+) calcd. for $C_{23}H_{23}FN_2O_3$ $[M+H]^+$ 383.1765, found 383.1768 (E = 0.38 ppm).

6-Benzyl-1-(3-(4-fluorophenyl)propyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (43)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 72 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.21 (m, 3H), 6.94 (m, 2H), 6.87 (t, *J* = 8.4 Hz, 2H), 6.75 (d, *J* = 7.8 Hz, 2H), 3.71 (s, 2H), 3.58 (t, *J* = 7.2 Hz, 2H), 2.78 (septet, *J* = 7.2 Hz, 1H), 2.46 (t, *J* = 7.2 Hz, 2H), 1.79 (m, 2H), 1.29 (d, *J* = 6.6 Hz, 6H); HRMS (ESI+) calcd. for $C_{23}H_{25}FN_2O_3$$[M+H]^+$ 397.1922, found 397.1924 (E = −0.51 ppm).

6-Benzyl-1-(4-(4-fluorophenyl)butyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (44)—This compound was prepared as a white solid following the procedure described for the preparation of **4.** Yield: 65 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.34 (t, *J* = 7.2 Hz, 2H), 7.28 (d, *J* = 7.8 Hz, 1H), 7.05 (m, 4H), 6.94 (t, *J* = 8.4 Hz, 2H), 3.92 (s, 2H), 3.73 (m, 2H), 2.87 (septet, *J* = 7.2 Hz, 1H), 2.51 (t, *J* = 7.2 Hz, 2H), 1.56 (m, 2H), 1.51 (m, 2H), 1.27 (d, *J* = 7.2 Hz, 6H); HRMS (ESI+) calcd. for $C_{24}H_{27}FN_2O_3$$[M+H]^+$ 411.2078, found 411.2081 (E = −0.62 ppm).

1-(Benzyloxymethyl)-6-(4-fluorobenzyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (51)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 74%; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.32-7.27 (m, 5H), 7.00-6.98 (m, 4H), 5.28 (s, 2H), 4.67 (s, 2H), 4.14 (s, 2H), 2.81 (septet, *J* = 7.2 Hz, 1H), 1.27 (d, *J* = 6.6 Hz, 6H); HRMS (ESI−) calcd. for $C_{22}H_{23}FN_2O_4$$[M-H]^-$ 399.1715, found 399.1706 (E = 2.1 ppm).

6-(4-Fluorobenzyl)-1-((4-fluorobenzyloxy)methyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (52)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 72%; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.28-7.27 (m, 6H), 7.00 (d, *J* = 7.2 Hz, 2H), 5.24 (s, 2H), 4.61 (s, 2H), 4.12 (s, 2H), 2.83 (septet, *J* = 7.2 Hz, 1H), 1.25 (d, *J* = 6.6 Hz, 6H); HRMS (ESI−) calcd. for $C_{22}H_{22}F_2N_2O_4[M-H]^-$ 417.1620, found 417.1620 (E = 0.10 ppm).

6-Benzyl-1-(benzyloxymethyl)-5-ethyl-3-hydroxypyrimidine-2,4(1H,3H)-dione (53)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 70 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.33-7.27 (m, 8H), 7.03 (d, *J* = 7.8 Hz, 2H), 5.26 (s, 2H), 4.65 (s, 2H), 4.15 (s, 2H), 2.51 (q, *J* = 7.8 Hz, 2H), 1.06 (t, *J* = 7.2 Hz, 3H); HRMS (ESI−) calcd. for $C_{21}H_{22}N_2O_4[M-H]^-$ 367.1652, found 367.1641 (E = 3.1 ppm).

1-(Benzyloxymethyl)-3-hydroxy-5-methylpyrimidine-2,4(1H,3H)-dione (54)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 37 %; ^{1} HNMR (600 MHz, $CDCl_3$) δ 7.32-7.28 (m, 5H), 7.06 (s, 1H), 5.25 (s, 2H), 4.60 (s, 2H), 1.93 (s, 3H); HRMS (ESI−) calcd. for $C_{13}H_{14}N_2O_4$ $[M-H]^-$ 263.1026, found 263.1023 (E = 1.3 ppm).

5-Benzyl-1-(benzyloxymethyl)-6-ethyl-3-hydroxypyrimidine-2,4(1H,3H)-dione (55)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 53%; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.22 (m, 4H), 7.19 (m, 3H), 7.12 (m, 3H), 5.42 (s, 2H), 4.61 (s, 2H), 3.76 (s, 2H), 2.68 (q, *J* = 7.2 Hz, 2H), 0.99 (t, *J* = 7.2 Hz, 3H); HRMS (ESI−) calcd. for $C_{21}H_{22}N_2O_4$ $[M-H]^-$ 365.1507, found 365.1484 (E = 6.2 ppm).

5-Benzyl-6-ethyl-1-((4-fluorobenzyloxy)methyl)-3-hydroxypyrimidine-2,4(1H,3H)-dione (56)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 59%; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.13 (m, 3H), 7.07 (m, 4H), 6.83 (t, *J* = 6.6 Hz, 2H), 5.28 (s, 2H), 4.48 (s, 2H), 3.67 (s, 2H), 2.72 (q, *J* = 6.6 Hz, 2H), 1.07 (t, *J* = 6.6 Hz, 3H); HRMS (ESI−) calcd. for $C_{21}H_{21}FN_2O_4[MH]^-$ 383.1485, found 383.1394 (E = 4.8 ppm).

1-Benzyl-6-(4-fluorobenzyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (64)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 70 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.33 (t, *J* = 7.2 Hz, 2H), 7.30 (m, 1H), 7.11 (d, *J* = 7.2 Hz, 2H), 7.06-7.04 (m, 2H), 7.02-7.00 (m, 2H), 4.98 (s, 2H), 3.86 (s, 2H), 2.84 (septet, *J* = 7.2 Hz, 1H), 1.29 (d, *J* = 6.6 Hz, 6H); HRMS (ESI+) calcd. for $C_{21}H_{21}FN_2O_3$ $[M+H]^+$ 369.1609, found 369.1606 (E = −1.9 ppm).

1,6-Bis(4-fluorobenzyl)-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (65)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 70 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.10-7.08 (m, 2H), 7.06-7.04 (m, 2H), 7.02-6.99 (m, 4H), 4.94 (s, 2H), 3.89 (s, 2H), 2.84 (septet, *J* = 7.2 Hz, 1H), 1.28 (d, *J* = 6.6 Hz, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 163.1 (d, *J* = 31.2 Hz), 162.2, 161.4 (d, *J* = 31.2 Hz), 151.8, 148.3, 132.2 (d, *J* = 3.3 Hz), 130.4 (d, *J* = 2.9 Hz), 128.6 (d, *J* = 7.8 Hz), 127.6 (d, *J* = 8.4 Hz), 119.7, 116.4 (d, *J* = 21.8 Hz), 116.1 (d, *J* = 21.8 Hz), 46.6, 33.6, 28.2, 20.4; HRMS (ESI+) calcd. for $C_{21}H_{20}F_2N_2O_3$ $[M+H]^+$ 387.1515, found 387.1502 (E = 3.3 ppm).

1,6-Bibenzyl-3-hydroxy-5-isopropylpyrimidine-2,4(1H,3H)-dione (66)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 53 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.39-7.34 (m, 4H), 7.32-7.30 (m, 2H), 7.12 (d, *J* = 7.2 Hz, 2H), 7.06 (d, *J* = 7.8 Hz, 2H), 5.00 (s, 2H), 3.91 (s, 2H), 2.90 (septet, *J* = 7.2 Hz, 1H), 1.29 (d, *J* = 7.2 Hz, 6H); HRMS (ESI+) calcd. for $C_{21}H_{22}N_2O_3$ $[M+H]^+$ 351.1703, found 351.1689 (E = 4.1 ppm).

1,6-Bibenzyl-5-ethyl-3-hydroxypyrimidine-2,4(1H,3H)-dione (67)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 43 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.31-7.27 (m, 3H), 7.26-7.23 (m, 3H), 7.04 (d, *J* = 6.6 Hz, 2H), 7.00 (d, *J* = 6.6 Hz, 2H), 4.91 (s, 2H), 3.80 (s, 2H), 2.47 (q, *J* = 7.2 Hz, 2H), 1.00 (t, *J* = 7.2 Hz, 3H); HRMS (ESI+) calcd. for $C_{20}H_{20}N_2O_3$ $[M+H]^+$ 337.1547, found 337.1534 (E = 3.8 ppm).

6-Benzyl-5-ethyl-1-(4-fluorobenzyl)-3-hydroxypyrimidine-2,4(1H,3H)-dione (68)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 48 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.38-7.35 (m, 2H), 7.32 (m, 1H), 7.15-7.13 (m, 2H), 7.07 (d, *J* = 7.8 Hz, 2H), 7.04 (m, 2H), 4.94 (s, 2H), 3.88 (s, 2H), 2.52 (q, *J* = 7.2 Hz, 2H), 1.07 (t, *J* = 7.2 Hz, 3H); HRMS (ESI+) calcd. for $C_{20}H_{19}FN_2O_3$ $[M+H]^+$ 355.1452, found 355.1442 (E = 3.0 ppm).

1-Benzyl-3-hydroxy-5-methylpyrimidine-2,4(1H,3H)-dione (69)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 32 %; ^{1}HNMR (600 MHz, $CDCl_3$) δ 7.35-7.31 (m, 3H), 7.28 (d, *J* = 7.2 Hz, 2H), 6.94 (s, 1H), 4.94 (s, 2H), 1.90 (s, 3H); HRMS (ESI+) calcd. for $C_{12}H_{12}N_2O_3$ $[M+H]^+$ 233.0921, found 233.0926 (E = −2.3 ppm).

1-(4-Fluorobenzyl)-3-hydroxy-5-methylpyrimidine-2,4(1H,3H)-dione (70)—This compound was prepared as a white solid following the procedure described for the preparation of **4**. Yield: 41 %; ^{1} HNMR (600 MHz, $CDCl_3$) δ 7.30-7.27 (m, 2H), 7.08-7.05 (m, 2H), 6.96 (s, 1H), 4.85 (s, 2H), 1.89 (s, 3H); HRMS (ESI−) calcd. for $C_{12}H_{11}FN_2O_3$ $[M-H]^-$ 251.0826, found 251.0822 (E = 1.8 ppm).

Biology

In Vitro Integrase Catalytic Assays—Expression and purification of the recombinant IN in Escherichia coli were performed as previously reported[28, 48] with addition of 10% glycerol to all buffers. Preparation of oligonucleotide substrates has been described.[49] Integrase reactions were performed in 10 μL with 400 nM of recombinant IN, 20 nM of 5′-end [^{32}P]-labeled oligonucleotide substrate and inhibitors at various concentrations. Solutions of 10% DMSO without inhibitors were used as controls. Reactions were incubated at 37 °C (60 minutes) in buffer containing 50 mM MOPS, pH 7.2, 7.5 mM $MgCl_2$, and 14.3 mM 2-mercaptoethanol. Reactions were stopped by addition of 10 μL of loading dye (10 mM EDTA, 98% deionized formamide, 0.025% xylene cyanol and 0.025% bromophenol blue). Reactions were then subjected to electrophoresis in 20% polyacrylamide–7 M urea gels. Gels were dried and reaction products were visualized and quantitated with a Typhoon 8600 (GE Healthcare, Little Chalfont, Buckinghamshire, UK). Densitometric analyses were performed using ImageQuant from Molecular Dynamics Inc. The concentrations at which enzyme activity was reduced by 50% (IC_{50}) were determined using “Prism” software (GraphPad Software, San Diego, CA) for nonlinear regression to fit dose-response data to logistic curve models.

HIV-1 Assay—The HIV Cytoprotection assay used CEM-SS cells and the IIIB strain of HIV-1. Briefly virus and cells were mixed in the presence of test compound and incubated for 6 days. The virus was pre-titered such that control wells exhibit 70 to 95% loss of cell viability due to virus replication. Therefore, antiviral effect or cytoprotection was observed when compounds prevent virus replication. Each assay plate contained cell control wells (cells only), virus control wells (cells plus virus), compound toxicity control wells (cells plus compound only), compound colorimetric control wells (compound only) as well as experimental wells (compound plus cells plus virus). Cytoprotection and compound cytotoxicity were assessed by MTS (CellTiter® 96 Reagent, Promega, Madison WI) and the EC_{50} (concentration inhibiting virus replication by 50%), CC_{50} (concentration resulting in 50% cell death) and a calculated TI (therapeutic index CC_{50}/EC_{50}) were provided. Each assay included the HIV RT inhibitor AZT as a positive control.

Modeling and docking—All modeling study was carried out using schrodinger modeling suite[50] based on our previous homology model[38] of HIV-1 IN CCD-DNA complex using Glide with standard precision protocol.[51] The Mg^{2+} ions and the interfacial hydrophobic pocket between the HIV-1 IN and DNA were defined as required constraints. The van der Waals radii of non-polar atoms for each of the ligands were scaled by a factor of 0.8 to account for structure variability to specific ligand binding. Validation of the docking protocol was carried out by re-docking both raltegravir and elvitegravir into the ligand binding site with structure comparison to the earlier reported mode of binding in PFV IN complex.[36] To further validate our structural model for HIV IN inhibitor design, correlation of the experimental and predicted IC_{50}s for a common mode of binding was performed for the most active compounds (**4**, **11**, **28**, **29**, **30**, **32**, **42**) based on linear reposnse method[52] implemented within Liason.[50]

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Abbreviations List

IN	integrase
HIV	human immunodeficiency virus
INI	integrase inhibitor
SAR	structure-activity-relationship
3′P	3′ processing
ST	strand transfer
DKA	diketoacid
HAART	highly active antiretroviral therapy
AIDS	acquired immunodeficiency syndrome
RT	reverse transcriptase

NTD	N-terminal domain
CCD	catalytic core domain
CTD	C-terminal domain
PFV	prototype foamy virus
***m*CPBA**	meta-chloroperbenzoic acid
CPE	cytopathic effect

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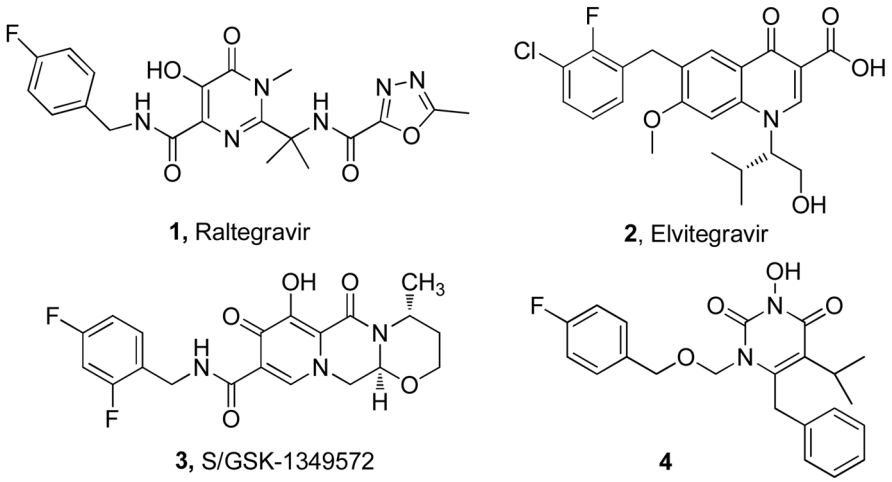


Figure 1.
Structures of best known INIs (**1**–**3**) and a novel INI (**4**).

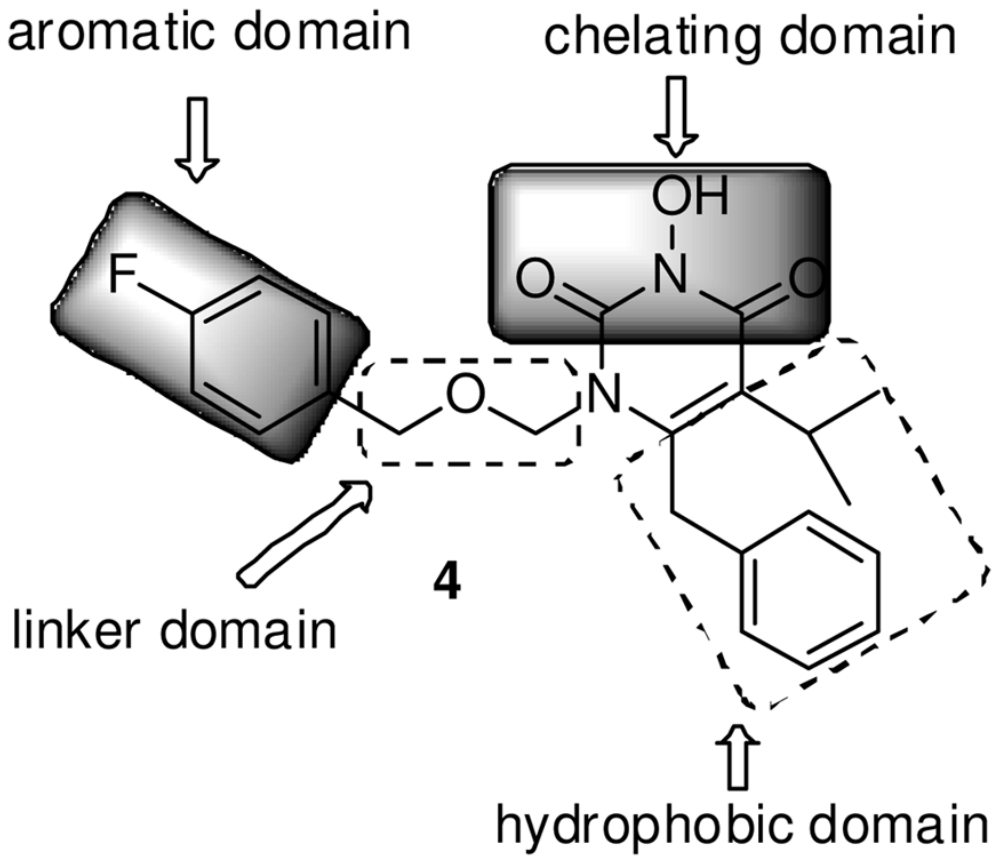


Figure 2.
SAR design of lead compound **4**. Major structural domains are highlighted.

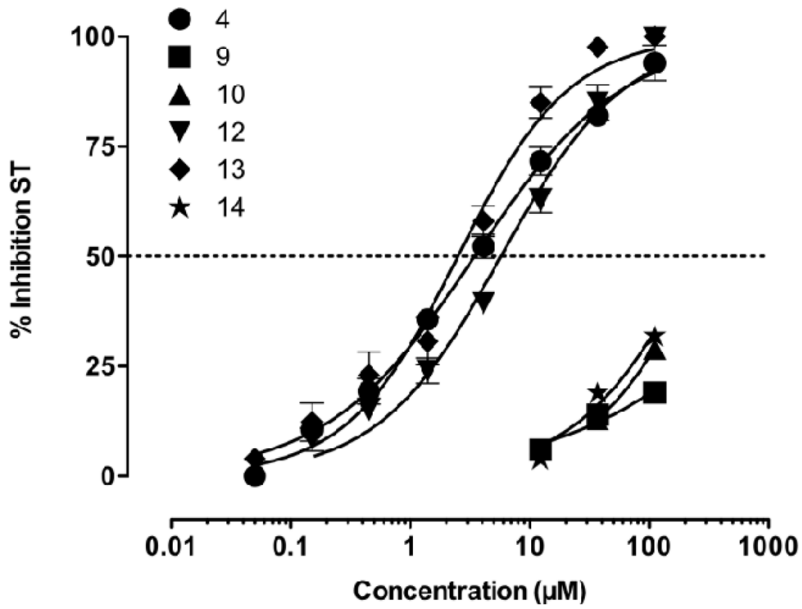


Figure 3.
Dose response curves of compounds **4**, **9**–**10** and **12**–**14**.

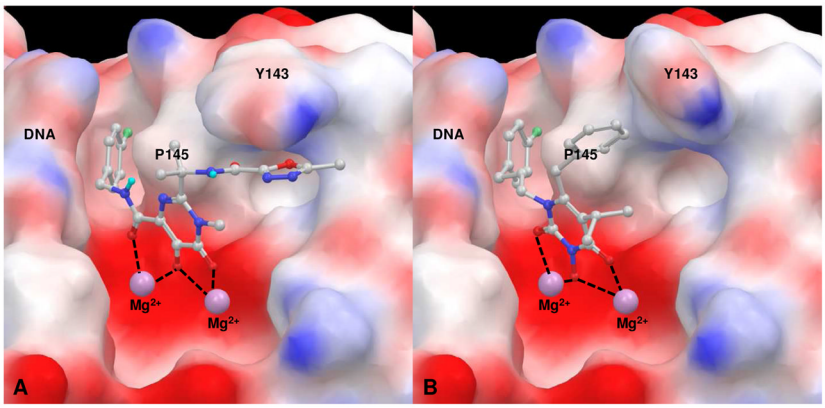


Figure 4.

Docking of raltegravir (**1**, A) and inhibitor **43** (B) in HIV-1 IN CCD in complex with Mg^{2+} and DNA. The 3-N hydroxyl group simultaneously chelates to both Mg^{2+} ions while allowing the placement of the benzyl group into the protein-DNA interfacial hydrophobic pocket.

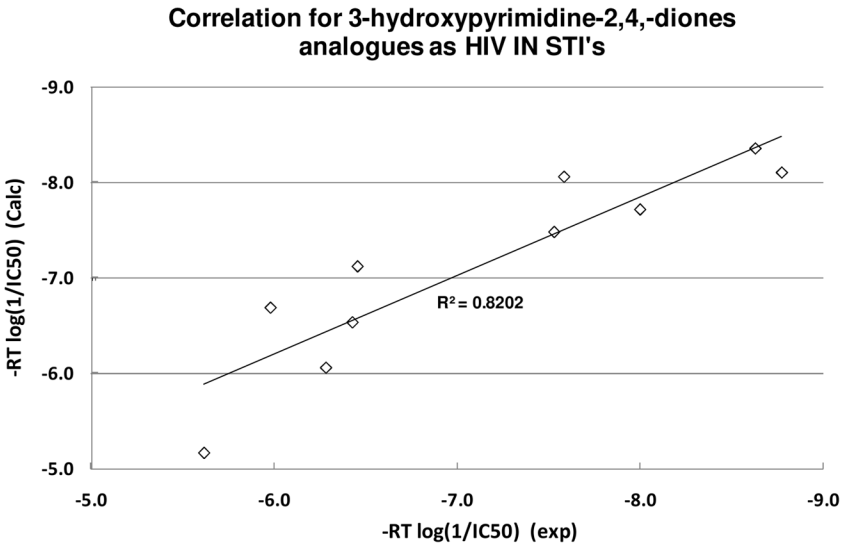
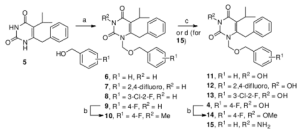


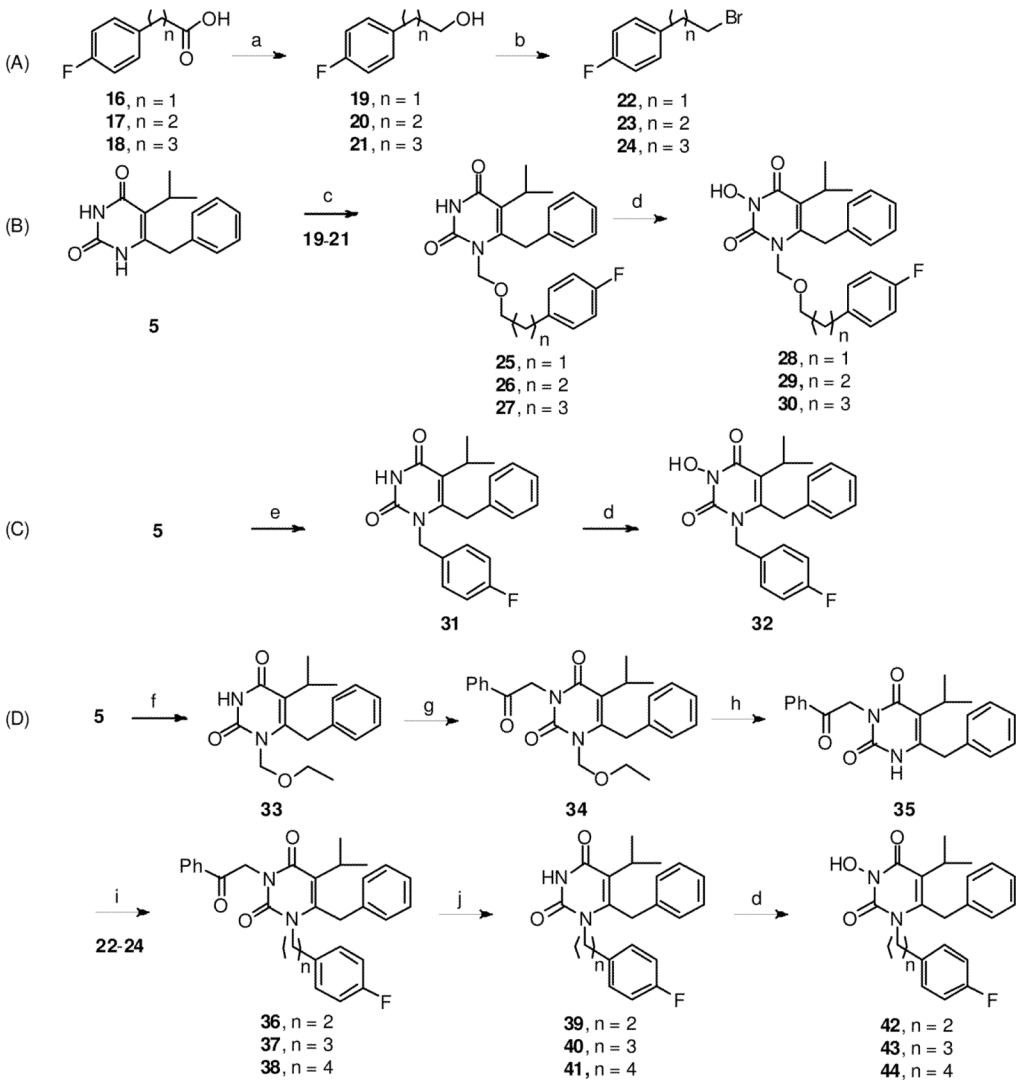
Figure 5.
Strong correlation of docked 3-hydroxypyrimidine-2,4,-diones analogues supports a common mode of binding for HIV IN STI design



Scheme 1.

[a] Synthesis of aromatic and chelating domains

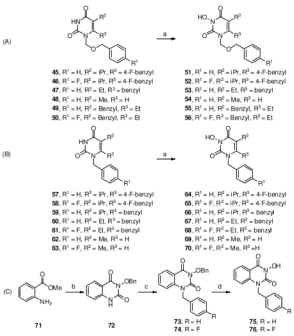
[a]Reagents and conditions: a) $CH_3C(OTMS)=NTMS$ (BSA), substituted benzyl alcohol, $(HCHO)_n$, TMSCl, TBAI (cat.), CH_2Cl_2, rt, 70–90%; b) Cs_2CO_3, THF, MeI, 40 °C, 53–63%; c) NaH, m-CPBA, THF, rt, 53–85%; d) NaH, MSH, THF, rt, 54%.



Scheme 2.

[a] Synthesis of linker domain

[a]Reagents and conditions: a) $LiAlH_4$, THF, rt, 67–72%; b) CBr_4, PPh_3, THF, rt, 73–80%; c) $CH_3C(OTMS)=NTMS$ (BSA), CH_2Cl_2; **19**–**21**, $(HCHO)_n$, TMSCl, TBAI (cat.), rt, 83–89%; d) NaH, m-CPBA, THF, rt, 62–72%; e) BSA, benzyl bromide, chlorobenzene, microwave, 160 °C, 50%; f) BSA, chloromethyl ethyl ether, TBAI (cat.), CH_2Cl_2, rt, 89%; g) K_2CO_3, $PhCOCH_2Br$, MeCN, reflux, 84%; h) TFA:H_2O (9:1), reflux, 76%; i) Cs_2CO_3, 4-F-$Ph(CH_2)_nBr$, DMF, 80 °C, 31–63%; j) Mg, AcOH, MeOH, rt, 48–57%.



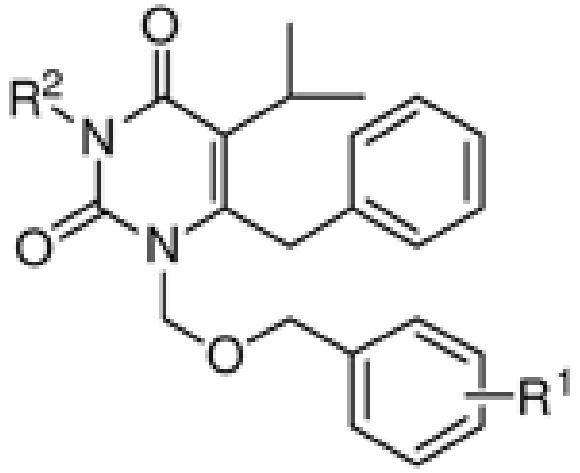
Scheme 3.

[a] Synthesis of hydrophobic domain

[a]Reagents and conditions: a) NaH, m-CPBA, THF, rt 32–72%; b) (i) CDI/toluene, reflux; then NH_2OBn, reflux; (ii) NaOH/EtOH, reflux, 53%; c) benzyl bromide or 4-Flurobenzyl bromide, Cs_2CO_3, DMF, 80 °C, 58–67%; d) HBr (48% in H_2O), reflux, 77–78%.

Table 1

Effects of aromatic and chelating domains on IN inhibition



Compd	R^1	R^2	IN IC_{50} (μM)[a]	
			3′P	ST[b]
11[c]	H	OH	>111	21 ± 2
12	2,4-F	OH	>111	4.8 ± 0.7
13	3-Cl-2-F	OH	>111	2.3 ± 0.6
4[c]	4-F	OH	>111	3.5 ± 0.6
9	4-F	H	>111	>111
10	4-F	Me	>111	>111
14	4-F	OMe	>111	>111
15[c]	H	NH_2	>111	>111

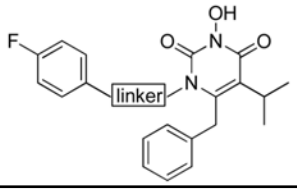
[a] Concentration inhibiting enzymatic function by 50%.

[b] Mean value ± standard deviation from triplicate experiments.

[c] Ref 30.

Table 2

Effects of linker domain on IN inhibition



		IN IC_{50} (μM)[a]	
Compd	**Linker**	**3′P**	**ST**[b]
4[c]	CH_2OCH_2	>111	3.5 ± 0.6
28	$(CH_2)_2OCH_2$	>111	1.6 ± 0.2
29	$(CH_2)_3OCH_2$	>111	3.2 ± 0.5
30	$(CH_2)_4OCH_2$	>111	4.5 ± 0.4
32	CH_2	>111	22 ± 0.5
42	$(CH_2)_2$	>111	46 ± 6
43	$(CH_2)_3$	>111	0.44 ± 0.1
44	$(CH_2)_4$	>111	0.56 ± 0.04

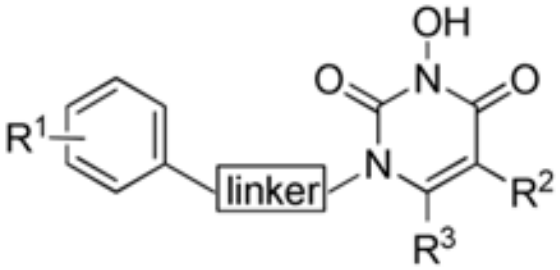
[a] Concentration inhibiting enzymatic function by 50%.

[b] Mean value ± standard deviation from triplicate experiments.

[c] Ref 30.

Table 3

Effects of hydrophobic domain on IN inhibition



					IN IC_{50} (μM)[a]	
Compd	**R^1**	**linker**	**R^2**	**R^3**	**3′P**	**ST[b]**
11[c]	H	CH_2OCH_2	*i*Pr	benzyl	>111	21 ± 2
51	H	CH_2OCH_2	*i*Pr	4-Fbenzyl	>111	7.3 ± 0.8
52	F	CH_2OCH_2	*i*Pr	4-Fbenzyl	>111	5.5 ± 0.7
53	H	CH_2OCH_2	Et	benzyl	>111	8.2 ± 1.0
54	H	CH_2OCH_2	Me	H	>111	75 ± 7
55	H	CH_2OCH_2	benzyl	Et	>111	36 ± 6
56	F	CH_2OCH_2	benzyl	Et	>111	11 ± 0.8
64	H	CH_2	*i*Pr	4-Fbenzyl	>111	32 ± 6
65	F	CH_2	*i*Pr	4-Fbenzyl	>111	73 ± 12
66	H	CH_2	*i*Pr	benzyl	>111	28 ± 2
67	H	CH_2	Et	benzyl	>111	>111
68	F	CH_2	Et	benzyl	>111	24 ± 3
69	H	CH_2	Me	H	>111	>111
70	F	CH_2	Me	H	>111	>111
75	H	CH_2	benzo (fused)		>111	>111
76	F	CH_2	benzo (fused)		>111	>111

[a] Concentration inhibiting enzymatic function by 50%.

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[b] Mean value ± standard deviation from triplicate experiments.

[c] Ref 30.

Table 4

Anti-HIV-1 activity of IN inhibitors

Compd	Single Concentration (10 μM)		Dose Response		
	CPE Reduction (%)[a]	Cell Viability (%)	EC_{50} (μM)[b]	CC_{50} (μM)[c]	TI[d]
4[e]	100	100	0.024	>20	>833
11[e]	100	100	0.0080	>20	>2,500
12	100	100	2.1	>100	>47
13	100	100	0.95	>100	>105
28	27	83	ND[f]	ND	--
29	30	92	ND	ND	--
30	12	88	ND	ND	--
43	12	97	ND	ND	--
44	6.0	94	ND	ND	--
49	48	100	ND	ND	--
50	10	92	ND	ND	--
51	100	100	1.1	>20	>18

[a] Reduction of viral cytopathic effect, indicating inhibitory activity of a compound.

[b] Concentration inhibiting virus replication by 50%.

[c] Concentration resulting in 50% cell death.

[d] Therapeutic index, defined by CC_{50}/EC_{50}.

[e] Ref 30.

[f] Not determined.

Table 5

Fold-resistance of inhibitors **4** and **13** against IN mutants

IN Mutants	Fold-resistance[a, b]		
	4[c]	**13**	**1**
G140S/Q148H	10/13	14/17	148/139
Y143R	7/4	7/5	24/28
N155H	5/6	5/7	10/8

[a] Fold-resistance is defined by $IC_{50(mutant)}/IC_{50\ (WT)}$.

[b] Values from two independent experiments.

[c] Ref 30.

Table 6

Fold-resistance of inhibitors **4** and **13** against raltegravir-resistant HIV-1 strains

Viruses	Major Mutations	Fold-resistance[a]		
		4[b]	**13**[c]	**1**
8070-2	G140S/Q148H	7.3	>2.0	>855
1556-1	Y143C	5.9	>1.7	>855
4736-2	N155H	3.1	>5.1	149

[a] Fold-resistance is defined by EC_{50}(mutant)/EC_{50} (WT).

[b] Ref 30.

[c] Toxicity observed (TC_{50} = 2.0 μM).