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Comparative Study of the Synthesis and Structural and Physicochemical Properties of Diketopiperazines vs Aza-diketopiperazines

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Lydia Karmazin, A. Ganesan, Dominique Bonnet

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A Comparative Study of the Synthesis, Structural and Physicochemical Properties of Diketopiperazines vs Aza-Diketopiperazines

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4 **Diketopiperazines vs Aza-Diketopiperazines**
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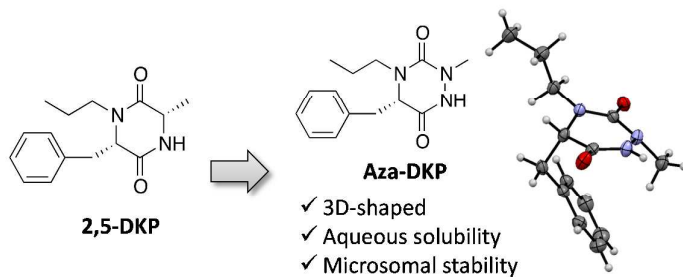
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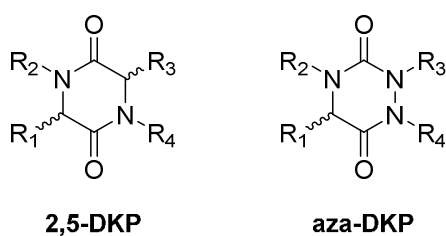


ABSTRACT

Aza-diketopiperazines (Aza-DKP) represent an underprivileged motif obtained by scaffold hopping of 2,5-diketopiperazines (2,5-DKP). Herein, we compare the synthesis but also the structural and the physicochemical properties of aza-DKP **4** vs 2,5-DKP **7**. Thus, X-ray and ¹H NMR studies show that aza-DKP **4** is a rigid and non-flat scaffold like the 2,5-DKP **7**. Moreover, the replacement of one C_α-stereogenic center by a nitrogen atom results in a significant improvement of both the water solubility and the microsomal stability.

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3 High-throughput screening is nowadays one of the most efficient methods to find new leads in
4 medicinal chemistry. Since the advent of combinatorial chemistry associated with solid
5 support synthesis, thousands of derivatives with the same scaffold have been synthesized
6 leading to scarce originality in chemical libraries.¹ Many libraries used in screening are often
7 populated by aromatic compounds which are planar, with low stereochemical complexity.²
8 This class of compounds may be suitable to target proteins such as kinases³ but scaffolds with
9 high content of sp^2 and sp hybridized carbons do not fit optimally with the spatial
10 configuration required for interaction with most biological receptors.^{4,5} Moreover, flat
11 aromatic structures are correlated with poorer specificity and physicochemical properties.
12 Lovering *et al.* have shown that compounds possessing a high fraction of sp^3 hybridized
13 carbons (F_{sp^3}) and chirality have a higher likelihood of progressing through the hit-to-drug
14 process.⁶ Therefore, there is a crucial need to enrich the chemical diversity of screening
15 libraries to facilitate the discovery of new drugs. In this context, scaffold hopping approaches
16 consisting in replacing the central core of a known active compound by a new scaffold able to
17 mimic the same biological interactions with the target could be used to improve both
18 pharmacodynamic and pharmacokinetic properties.⁷ In the course of the discovery of new
19 scaffolds relevant for medicinal chemistry, we can also list as selection criteria a low
20 molecular weight to allow substitutions while keeping the molecular weight below 500 g.mol⁻¹,
21 and the rigidity of these platforms that can adopt a well-defined and three-dimensional (3D)
22 orientation of their substituents. 2,5-Diketopiperazines (2,5-DKP) fulfill these criteria since
23 they have a low molecular weight and a constrained structure providing a non-planar system
24 that directs its four potential substituents in different vectors in 3D-space. 2,5-DKP is a well-
25 known and privileged scaffold in medicinal chemistry as examples are able to interact with
26 many biological targets.⁸ While this scaffold has received great attention and is thus described
27 in numerous patents making its exploitation difficult, scaffold hopping by introduction of an
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3 additional nitrogen gives the much less studied heterocycle 1,2,4-triazine-3,6-dione or aza-
4 diketopiperazine (aza-DKP, Figure 1). Indeed, very few efficient syntheses with broad scope
5 are available for the preparation of this rare heterocycle.⁹⁻¹⁴ Aza-DKPs have been obtained
6 from N-(mesyloxy)malonamide reacting with hydrazines,⁹ by using triphosgene and gaseous
7 HCl to form aza-DKPs from N-Boc hydrazides,⁹ by using triphosgene and gaseous
8 HCl to form aza-DKPs from N-Boc hydrazides,¹⁰ from semicarbazone in acidic conditions¹¹
9 and by a recent one-pot sequence involving nitrogen-substituted isocyanates as key
10 intermediates.¹² However, these approaches enable the synthesis of disubstituted aza-DKPs
11 only and/or very limited trisubstituted analogs. Thereby, to prepare more complex aza-DKPs
12 and facilitate the preparation of diversity-oriented libraries, our group has recently reported a
13 convenient solution- and solid-phase strategy from α -aminoesters and N-Boc hydrazides,¹³
14 and a step-economical multicomponent process driven by Rh(I)-catalyzed hydroformylation
15 of alkenylsemicarbazides.¹⁴ Interestingly, the replacement of one carbon by a planar nitrogen
16 atom may have a deep influence on the chemical and pharmacological properties of DKP.
17 Herein, we evaluate the synthesis and the structural and physicochemical properties of aza-
18 DKP as compared to 2,5-DKP.

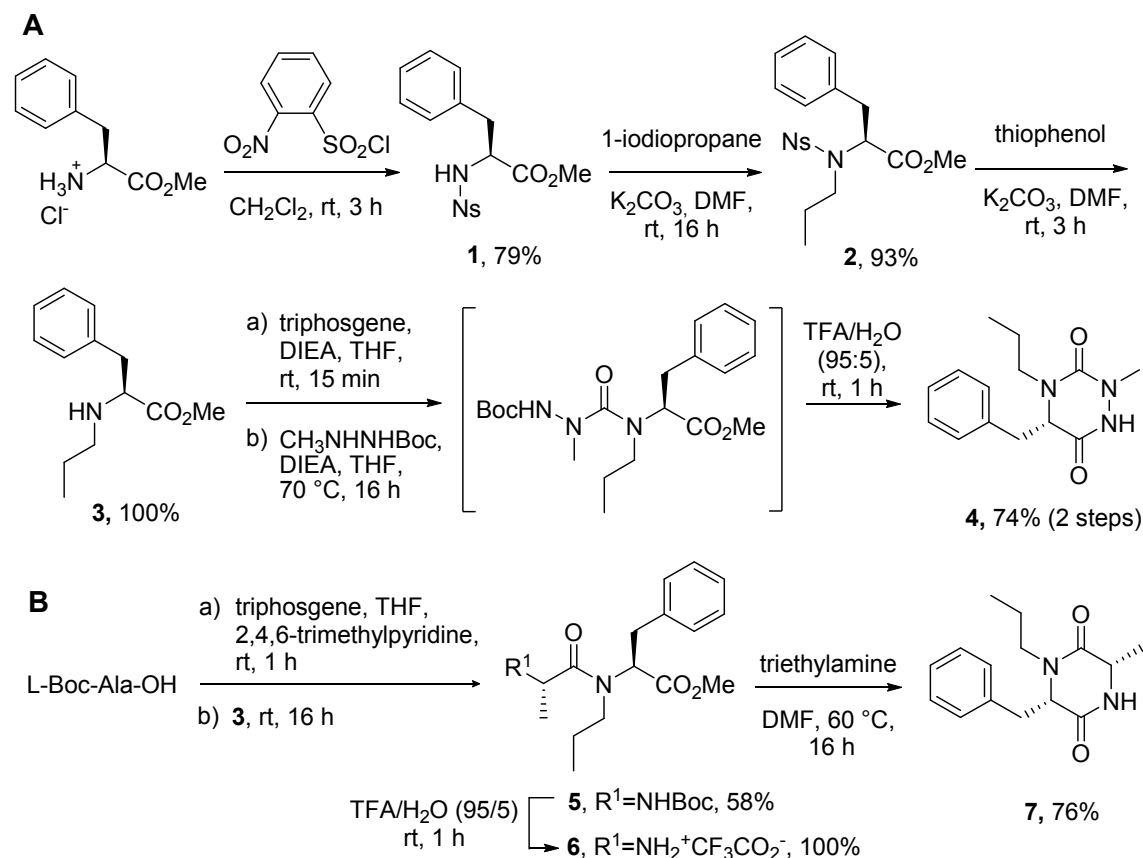


44 **Figure 1.** Generic structure of 2,5-DKP and aza-DKP

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47 In order to study the impact of the substitution of the α -carbon by a nitrogen atom on both the
48 physicochemical and structural parameters, we compared aza-DKP **4** and its 2,5-DKP analog
49 **7**. The aza-DKP synthesis began with L-phenylalanine which was first protected using nosyl
50 chloride (Scheme 1). Then, the amine **1** was monoalkylated with propyl iodide under mild
51 conditions using Fukuyama's sulfonamide method.¹⁵ Deprotection of **2** with thiophenol gave
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3 **3** with an overall yield of 73% from L-phenylalanine.¹⁶ A subsequent, activation of **3** with
4 triphosgene followed by a treatment with 1-*N*-Boc-2-methylhydrazine provided the
5 corresponding semicarbazide. In the presence of TFA/water (95/5, v/v), the crude mixture was
6
7 then readily converted into aza-DKP **4** following a deprotection/cyclization process.¹⁴ To
8
9 synthesize the 2,5-DKP analog, alkyl amine **3** was coupled with *N*-Boc-L-alanine. The
10
11 resulting linear dipeptide **5** was then treated with a solution of TFA/H₂O (95:5) to initiate the
12
13 deprotection/cyclization towards the corresponding 2,5-DKP. However, the acidic treatment
14
15 only resulted in the quantitative deprotection to amine **6** which did not cyclize. This difference
16
17 of reactivity between the linear dipeptide **5** and the deprotected semicarbazide may be due to
18
19 the α -effect and lower basicity of the hydrazine moiety leading to a more nucleophilic β -
20
21 nitrogen that favors the cyclization in acidic catalysis. Nevertheless, a basic treatment with
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23 triethylamine in DMF at 60 °C resulted in the cyclization of **6** affording the 2,5-DKP **7** in a
24
25 good yield (76%).¹⁷ The overall yield for the synthesis of aza-DKP **7** is higher than that
26
27 obtained for 2,5-DKP **7** (54% vs 32% from L-phenylalanine). As compared to 2,5-DKP **7**, the
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29 synthesis of aza-DKP **4** is more rapid and performed at room temperature that makes easier
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31 the access to chemical libraries.
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Scheme 1. Synthesis of aza-DKP 4 (A) and 2,5-DKP 7 (B)



Both aza-DKP 4 and 2,5-DKP 7 were crystalline materials that were suitable for obtaining single-crystal X-ray diffraction structures.¹⁸ Despite the substitution of a carbon by a nitrogen atom in the central core, both compounds clearly display similarities in the spatial orientation of the three substituents in space (Figure 2). However, some subtle structural differences were observed. Indeed, the conformation of the aza-DKP 4 is a flattened pseudo-boat shape with N2-N1-C1-N3 and N2-C2-C3-N3 dihedral angles of $-4.2(3)^\circ$ and $-22.2(2)^\circ$, respectively whereas the conformation of the 2,5-DKP 7 is a flattened boat shape with N1-C2-C1-N2 and N1-C3-C4-N2 dihedral angles of $-10.1(3)^\circ$ and $-11.1(3)^\circ$, respectively. In both compounds, the benzyl moiety is in an axial orientation on the same side as the methyl substituent while the propyl group is orientated on the other side to avoid a steric clash.

Moreover, the X-ray structure of aza-DKP **4** shows that the methyl moiety is notably deviated from the N2-N1-C1 plane with an angle of 27.1(2)° and adopts a pseudo-axial position. The propyl moiety linked to N3 is diverted with an angle of 18.7(2)° from the C1-N3-C3 plane and the hydrogen atom on N2 is diverted with an angle of 6.0(2)° from the N1-N2-C2 plane. For the 2,5-DKP **7**, the deviation for the methyl moiety is more important (48.1(2)° from the C1-C2-N1 plane), the other deviations are moderate (2.7(2)° for the propyl moiety from the C1-N2-C4 plane, and 12.2(19)° for the hydrogen atom carried by N1 from the C2-N1-C3 plane) relative to the aza-DKP **4**. Interestingly N1 of the aza-DKP ring adopts a partial sp³ hybridization as observed for aza-peptides.¹⁹ Examination of the distance between N1 and the plane formed by N2, C1, C2 and C3 indicates a S-configuration with a 0.229(2) Å distortion from planarity.

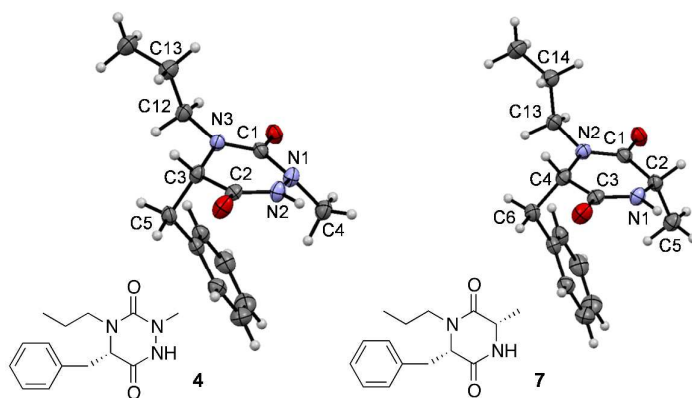


Figure 2. X-ray structures of aza-DKP **4** and 2,5-DKP **7**

The spatial configuration of 2,5-DKP **7** has previously been studied and shown to be a rigid structure.²⁰ Malavašič *et al.* have published that according to ¹H NMR, the chemical shift of the methyl group protons at C2 in 2,5-DKP **7** is unusually low, around 0.8 ppm in DMSO at 298 K, whereas the signal of these protons in 2,5-DKP without the benzyl group appears between 1.40 ppm and 1.54 ppm. These data are in accordance with the crystallographic structure of 2,5-DKP **7** which has displayed a spatial proximity of the methyl protons with the aromatic ring allowing π - σ interaction.²⁰ In order to investigate the spatial organization of the

aza-DKP **4**, a ^1H NMR study was performed in CDCl_3 , a non-polar solvent, and in DMSO, a polar aprotic solvent (Figure 3).

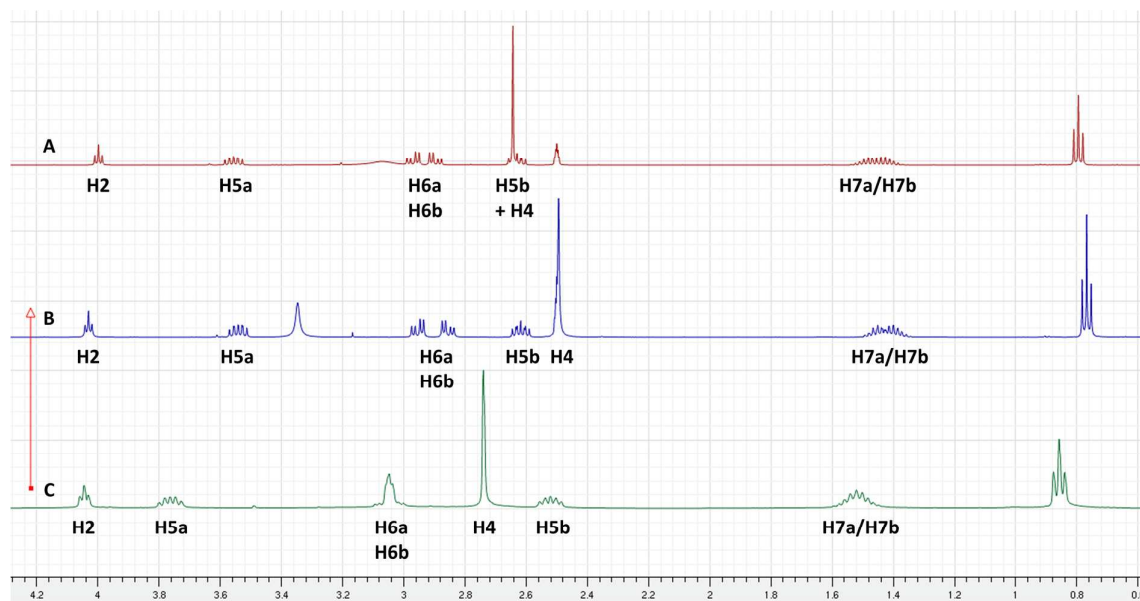


Figure 3. ^1H NMR spectra of aza-DKP **4** in DMSO at 363 K (A), in DMSO at 298 K (B) and in CDCl_3 at 298 K (C).

In the spectra, the two protons H12 (H12a and H12b) of the propyl chain appear as an AX_2Y spin system. Furthermore, their chemical shifts were significantly different as their signals were at 3.75 ppm and 2.51 ppm in CDCl_3 and at 3.55 ppm and 2.62 ppm in DMSO at 298 K. The increase of the temperature from 298 K to 363 K had no effect on the chemical shift of these protons. Thus, these two protons are in a different magnetic environment indicating that the rotation of the propyl group is slow on the NMR time-scale. In addition, the chemical shift of the methyl group (H4) is shifted to low field (2.73 ppm in CDCl_3 and 2.49 ppm in DMSO at 298 K). As observed for 2,5-DKP **7**, this could be explained by shielding of these protons by the proximal benzyl moiety. The chemical shift of these methyl protons was slightly affected by the increase of temperature (2.49 ppm at 298 K to 2.64 ppm at 363 K).

Thus, the nature of the solvent and the temperature have a low impact on the chemical shift of the protons and consequently on the conformation of the aza-DKP scaffold. According to our

X-ray and NMR data, aza-DKP **4** displays a rigid structure that prevents the propyl chain rotation and blocks the methyl group on the same side as the benzyl ring. Thus, the ability of aza-DKP scaffold to efficiently orientate its substituents in different planes of 3D-space should be an advantage for drug discovery by optimizing interaction with biological targets.²¹ On the other hand, in comparison to DKP, the aza-DKP scaffold may undergo adaptive chirality as previously reported.²²

Regarding the drug-like properties, aza-DKP **4** and 2,5-DKP **7** have a low polar surface area and molecular weight, less than five hydrogen bond acceptors and only one hydrogen bond donor in accordance with Lipinski rules and other guidelines for oral bioavailability.²³ Some physicochemical properties of aza-DKP **4** and 2,5-DKP **7** were then assessed (Table 1). Thermodynamic solubility studies in a pH 7.4 PBS buffer showed that the additional nitrogen atom on aza-DKP **4** had a significant effect on the compound solvation. Indeed, a 17-fold increase was observed on the aqueous solubility of aza-DKP **4** as compared to 2,5-DKP **7** (16.5 mM vs 0.98 mM, respectively). Moreover, $\log D_{7.4}$ was lowered enabling the introduction of non-polar substitutions on this scaffold while keeping an acceptable distribution coefficient during the optimization process for drug discovery purposes.

Table 1. Drug-like Properties and Physicochemical Parameters of aza-DKP **4** and 2,5-DKP **7**

| Parameters | Aza-DKP 4 | 2,5-DKP 7 |
|---|------------------|------------------|
| Molecular weight (g/mol) | 261.3 | 260.3 |
| Polar surface area (Å ²) ^a | 52.65 | 49.41 |
| H-bond acceptor | 5 | 4 |
| H-bond donor | 1 | 1 |
| Rotatable bond | 4 | 4 |
| Solubility (mM) ^b | 16.5 ± 0.6 | 0.98 ± 0.06 |
| LogD _{7.4} | 1.06 ± 0.03 | 1.38 ± 0.13 |

^aPolar surface area calculated by ChemAxon software. ^bThermodynamic solubility measured in a pH 7.4 phosphate-buffered saline.

The chemical and metabolic stabilities of Aza-DKP **4** and 2,5-DKP **7** were also studied (Table 2). After 24 h of incubation in PBS buffer, these two compounds were fully stable. Similarly, Aza-DKP **4** and 2,5-DKP **7** remained perfectly intact in plasma after 6 h of exposure in spite of the presence of amidases. In mouse liver microsomes, the aza-DKP **4** was found to be more stable than the 2,5-DKP **7** after 30 min of incubation (83% vs 51% remaining) indicating the biological robustness of this new scaffold.

Table 2. Chemical and Metabolic Stability of aza-DKP **4** and 2,5-DKP **7**

| Stability ^a | Aza-DKP 4 % | 2,5-DKP 7 % |
|-------------------------|-----------------------|-----------------------|
| PBS ^b | > 98 | > 98 |
| Plasma ^c | > 98 | > 98 |
| Microsomes ^d | 83 ± 3 | 51 ± 1 |

^aPercent of remaining starting compounds. ^bpH 7.4 phosphate-buffered saline after 24 h.

^cMouse plasma after 6 h at 37 °C. ^dMouse hepatocytes after 30 min at 37 °C.

In conclusion, the comparison between 2,5-DKP and aza-counterpart offers an interesting insight regarding the synthesis, the conformation and pharmacokinetic properties of the latter. Relying on an efficient and rapid deprotection/cyclization process, aza-DKP was obtained at room temperature and with a higher yield than 2,5-DKP. As shown by X-ray analysis and ¹H NMR study, aza-DKP displayed a structure close to 2,5-DKP despite the replacement of one tetrahedral carbon by a nitrogen atom. Interestingly, this aza-heterocycle exhibited a rigid backbone directing its substituents in different directions of 3D-space. This non-planar scaffold provides a new opportunities to improve drug-target interactions and success in clinical studies.⁶ Furthermore, the presence of the nitrogen atom significantly improved aqueous solubility and distribution coefficient compared to its 2,5-DKP analog allowing the substitution with more hydrophobic groups during the optimization process to increase the biological activity. Metabolic stability was also significantly enhanced thanks to this scaffold

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3 as compared to the 2,5-DKP analog. In summary, we demonstrated that aza-DKP is an
4 original heterocycle, readily accessible from simple building blocks, giving new opportunities
5 in medicinal chemistry by mimicking the structural architecture of 2,5-DKP while it may
6 improve patentability and physicochemical and pharmacokinetic properties.
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11 12 13 14 **EXPERIMENTAL SECTION**

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16 General methods. Reagents, dry solvents and deuterated solvents were obtained from
17 commercial sources and used without any further purification. Thin-layer chromatography
18 was performed on silica gel 60 F₂₅₄ plates.
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22 Flash chromatography was performed on silica gel pre-packed columns RP18 (30 mm).
23 Analytical reverse-phase high-performance liquid chromatography (RP-HPLC) separations
24 were performed on a C18 column (2.7 μ m, 4.6 mm x 75 mm) using a linear gradient (5 % to
25 95 % of solvent B in solvent A in 7 min, flow rate 1.6 mL/min), detection at 220 nm, solvent
26 A : water/0.1 % trifluoroacetic acid (TFA), solvent B : acetonitrile/0.1 % TFA).
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34 Semi-preparative reverse-phase high-performance liquid chromatography (RP-HPLC)
35 separations were performed on a RP-C18 column (7 μ m, 19 mm x 300 mm).
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39 ¹H and ¹³C NMR spectra were recorded on a 500 MHz/125 MHz and 400 MHz/100 MHz
40 spectrometer. Conditions are specified for each spectrum (temperature 25 °C unless
41 specified). Chemical shifts are reported in parts per million (ppm) relative to residual solvent
42 and coupling constants (*J*) are reported in hertz (Hz). Signals are described as s (singlet), d
43 (doublet), t (triplet), m (multiplet), dd (doublet of doublets), ddd (doublet of doublet of
44 doublets), qd (quartet of doublets) and br s (broad singlet).
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52 HRMS were obtained on a Q-ToF LC/MC apparatus using electrospray ionization mode and
53 time-of flight analyzer (ESI-TOF).
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57 Melting points were determined in open capillary tubes. Specific rotations were measured
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3 using a 10 cm cell with a Na 589 nm filter.
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7 **Methyl ((2-nitrophenyl)sulfonyl)-L-phenylalaninate 1.** To a solution of methyl *L*-
8 phenylalaninate hydrochloride (2.40 g, 11.1 mmol, 1 equiv) and NEt₃ (4.64 mL, 33.4 mmol, 3
9 equiv) in CH₂Cl₂ (60 mL) was added 2-nitrobenzenesulfonyl chloride (3.70 g, 16.7 mmol, 1.5
10 equiv). The mixture was stirred for 3 h at rt. The organic layer was washed with a solution of
11 NaHCO₃, water and NaCl. The organic layer was dried on anhydrous Na₂SO₄ and evaporated.
12 The residue was purified on silica gel column eluting with 20-40% EtOAc in *n*-heptane (R_f
13 0.18, 40% EtOAc in *n*-heptane) to afford the desired product (3.20 g, 8.78 mmol, 79%) as a
14 light yellow oil: [α]_D²⁰ = -89.2 °(c 0.19, CDCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.93-7.90
15 (m, 1H), 7.81-7.78 (m, 1H), 7.68-7.59 (m, 2H), 7.21-7.04 (m, 5H), 6.02 (d, *J* = 8.7 Hz, 1H),
16 4.44 (ddd, *J* = 8.7, 7.1, 5.6 Hz, 1H), 3.50 (s, 3H), 3.14 (dd, *J* = 13.9, 5.6 Hz, 1H), 3.04 (dd, *J* =
17 13.9, 7.1 Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 170.9, 147.5, 135.0, 134.0, 133.7, 133.1,
18 130.4, 129.3, 128.7, 127.5, 125.6, 57.9, 52.6, 39.2; HRMS (ESI-TOF) calcd for
19 C₁₆H₁₆N₂O₆SNa [M+Na]⁺ 387.06214, found 387.06233.
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38 **Methyl *N*-((2-nitrophenyl)sulfonyl)-*N*-propyl-*L*-phenylalaninate 2.** To a mixture of methyl
39 ((2-nitrophenyl)sulfonyl)-*L*-phenylalaninate (3.00 g, 8.23 mmol, 1 equiv) and K₂CO₃ (2.28 g,
40 16.5 mmol, 2 equiv) in DMF (40 mL), 1-iodopropane (1.61 mL, 16.5 mmol, 2 equiv) was
41 added. The mixture was stirred for 16 h at rt and evaporated. The residue was purified on
42 silica gel column eluting with 20-40% EtOAc in *n*-heptane (R_f 0.38, 40% EtOAc in *n*-
43 heptane) to afford the desired product (3.12 g, 7.68 mmol, 93%) as a light yellow oil:
44 [α]_D²⁰ = -25.8 °(c 0.22, CDCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.82-7.78 (m, 1H), 6.66-6.51
45 (m, 3H), 7.28-7.16 (m, 5H), 4.86 (t, *J* = 7.6 Hz, 1H), 3.52 (s, 3H), 3.45-3.32 (m, 2H), 3.26-
46 3.16 (m, 1H), 3.01 (dd, *J* = 14.1, 7.2 Hz, 1H), 1.70-1.52 (m, 2H), 0.86 (t, *J* = 7.4 Hz, 3H); ¹³C
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3 NMR (100 MHz, CDCl₃) δ 170.8, 148.3, 136.6, 133.7, 133.3, 131.6, 130.9, 129.3, 128.7,
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5 127.1, 124.1, 61.4, 52.4, 48.4, 36.9, 23.8, 11.5; HRMS (ESI-TOF) calcd for C₁₉H₂₂N₂O₆SNa
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7 [M+Na]⁺ 429.10908, found 429.11023.
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11 **Methyl propyl-*L*-phenylalaninate 3.**²⁰ To a solution of methyl *N*-((2-nitrophenyl)sulfonyl)-
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13 *N*-propyl-*L*-phenylalaninate (3.10 g, 7.63 mmol, 1 equiv) and thiophenol (1.17 mL, 11.4
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15 mmol, 1.5 equiv) in DMF (41 mL), K₂CO₃ (2.11 g, 15.3 mmol, 2 equiv) was added. The
16
17 mixture was stirred at rt for 3 h and evaporated. Purification on silica gel column eluting with
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19 20-40% EtOAc in *n*-heptane (R_f 0.32, 30% EtOAc in *n*-heptane) afforded the desired product
20
21 (1.69 g, 7.63 mmol, 100%) as a clear oil. ¹H NMR (400 MHz, CDCl₃) δ 7.34-7.15 (m, 5H),
22
23 3.66 (s, 3H), 3.54 (t, *J* = 7.0 Hz, 1H), 2.97 (dd, *J* = 7.0, 2.9 Hz, 2H), 2.60-2.53 (m, 1H), 2.49-
24
25 2.41 (m, 1H), 1.55-1.41 (m, 3H), 0.88 (t, *J* = 7.0 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ
26
27 175.2, 137.4, 129.1, 128.4, 126.7, 63.2, 51.6, 50.2, 39.8, 23.2, 11.6; LRMS (ESI-TOF) *m/z* =
28
29 222.2 [M+H]⁺.
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36 **(*S*)-5-Benzyl-2-methyl-4-propyl-1,2,4-triazinane-3,6-dione 4.** To a solution of triphosgene
37
38 (270 mg, 0.91 mmol, 0.335 equiv) in anhydrous THF (16.3 mL), under argon, a solution of *N*-
39
40 propyl *L*-phenylalanine methyl ester (601 mg, 2.72 mmol, 1 equiv) and DIEA (520 μL, 2.99
41
42 mmol, 1.1 equiv) in anhydrous THF (6.8 mL) was added dropwise (over 5 minutes). The
43
44 mixture was stirred at rt for 15 minutes. A solution of *tert*-butyl 2-methylhydrazine-1-
45
46 carboxylate (397 mg, 2.72 mmol, 1 equiv) and DIEA (520 μL, 2.99 mmol, 1.1 equiv) in
47
48 anhydrous THF (4.0 mL) was added dropwise. The mixture was heated at 40 °C overnight
49
50 and evaporated *in vacuo*. The crude was then treated with a solution of TFA/H₂O (95:5, 2
51
52 mL) for 1 h at room temperature and concentrated under reduced pressure. Purification on
53
54 silica gel column eluting with a gradient of 20% EtOAc in *n*-heptane (R_f 0.22) afforded 525
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3 mg (2.01 mmol, 74%) of the title compound as a white solid: mp 140.7-142.7 °C; $[\alpha]_{\text{D}}^{20} =$
4
5 +9.8 (*c* 0.2, MeOH); ^1H NMR (400 MHz, CDCl_3) δ 7.43-7.16 (m, 5H), 4.07-4.01 (m, 1H),
6
7 3.82-3.70 (m, 1H), 3.11-2.98 (m, 2H), 2.74 (s, 3H), 2.57-2.47 (m, 2H), 1.61-1.43 (m, 2H),
8
9 0.89-0.82 (m, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 165.3, 153.8, 135.4, 129.9, 128.9, 127.5,
10
11 61.8, 48.1, 36.2, 34.8, 21.5, 11.3; HRMS (ESI-TOF) calcd for $\text{C}_{14}\text{H}_{20}\text{N}_3\text{O}_2$ ($\text{M}+\text{H}$)⁺
12
13 262.15500, found 262.15485.
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18 **Methyl *N*-((*tert*-butoxycarbonyl)-*L*-alanyl)-*N*-propyl-*L*-phenylalaninate 5.** (*tert*-
19
20 Butoxycarbonyl)-*L*-alanine (339 mg, 1.79 mmol, 1 equiv) was dissolved in anhydrous THF (5
21
22 mL). 2,4,6-Collidine (954 μL , 7.17 mmol, 4 equiv) and BTC (213 mg, 0.72 mmol, 0.4 equiv)
23
24 were added to the mixture, which was allowed to stir at rt for 5 min. A solution of methyl
25
26 propyl-*L*-phenylalaninate (462 mg, 1.79 mmol, 1 equiv) in anhydrous THF (5 mL) was added
27
28 and the mixture was stirred at rt for 16 h. The mixture was evaporated under reduced pressure.
29
30 The residue was purified on silica gel eluting with a gradient of 30-60% EtOAc in *n*-heptane
31
32 followed by a purification on flash chromatography with 5-100% MeCN in water (R_f 0.29,
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34 50% EtOAc in *n*-heptane) to afford the desired product as a white solid (406 mg, 1.03 mmol,
35
36 58%): mp 99.8 - 101.8 °C; $[\alpha]_{\text{D}}^{20} = -181.4$ (*c* 0.17, MeOH); ^1H NMR (500 MHz, $\text{DMSO-}d_6$,
37
38 70 °C) δ 7.33-7.13 (m, 5H), 6.44 (br s, 1H), 4.36-4.21 (m, 2H), 3.59 (s, 3H), 3.25 (dd, $J =$
39
40 14.0, 5.0 Hz, 1H), 3.17-3.00 (m, 2H), 2.72-2.62 (m, 1H), 1.45-1.34 (m, 11H), 1.11 (d, $J = 6.9$
41
42 Hz, 3H), 0.74 (t, $J = 7.3$ Hz, 3H); ^{13}C NMR (125 MHz, $\text{DMSO-}d_6$) δ 172.6, 170.8, 154.8,
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44 138.1, 129.3, 128.1, 126.4, 77.8, 61.6, 51.5, 51.1, 46.1, 34.0, 28.1, 21.3, 17.9, 10.8; HRMS
45
46 (ESI-TOF) calcd for $\text{C}_{21}\text{H}_{32}\text{N}_2\text{O}_5\text{Na}$ ($\text{M}+\text{Na}$)⁺ 415.22035, found 415.22041.
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54 **(*S*)-1-(((*S*)-1-Methoxy-1-oxo-3-phenylpropan-2-yl)(propyl)amino)-1-oxopropan-2-**
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56 **aminium 2,2,2-trifluoroacetate 6.** Methyl *N*-((*tert*-butoxycarbonyl)-*L*-alanyl)-*N*-propyl-*L*-
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phenylalaninate (373 mg, 0.95 mmol, 1 equiv) was solubilized in a mixture of trifluoroacetic acid and water (2.1 mL, 95:5). The mixture was allowed to stir at rt at 0 °C for 1 h and was then evaporated to a slurry (386 mg, 0.95 mmol, 100%). Analysis of the crude product by NMR showed only trifluoroacetate **6** without product from cyclisation. ¹H NMR (400 MHz, CDCl₃) δ 7.71 (br s, 3H), 7.26-6.96 (m, 5H), 4.31-4.20 (m, 1H), 3.86 (dd, *J* = 10.9, 4.8 Hz, 1H), 3.60 (s, 3H), 3.31-3.12 (m, 2H), 2.93-2.81 (m, 1H), 2.37-2.25 (m, 1H), 1.42-1.26 (m, 5H), 0.67 (t, *J* = 7.3 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 170.9, 169.6, 161.2 (q, *J* = 38 Hz), 136.9, 129.3, 129.0, 127.5, 115.5 (q, *J* = 288 Hz), 63.6, 52.9, 52.5, 48.0, 34.3, 21.5, 17.0, 10.6; HRMS (ESI-TOF) calcd for C₁₆H₂₅N₂O₃ (M+H)⁺ 293.186518, found 293.186546.

(3*S*,6*S*)-6-Benzyl-3-methyl-1-propylpiperazine-2,5-dione **7**.²⁰ (*S*)-1-(((*S*)-1-Methoxy-1-oxo-3-phenylpropan-2-yl)(propyl)amino)-1-oxopropan-2-aminium 2,2,2-trifluoroacetate **4** (227 mg, 0.68 mmol, 1 equiv) and Et₃N (380 μL, 2.74 mmol, 4 equiv) were dissolved in DMF (5 mL). The mixture warmed to 60 °C and stirred overnight. The mixture was then evaporated to a slurry. The residue was purified on flash chromatography eluting with 5-100% MeCN in water (*R*_f 0.34, 5% MeOH/CH₂Cl₂) to afford 135 mg (0.52 mmol, 76%) of the desired product as a white solid: mp 218.3–220.3 °C, lit 221 - 223 °C; [*α*]_D²⁰ = +56.0 (*c* 0.50, CH₂Cl₂); ¹H NMR (400 MHz, DMSO-*d*₆) δ 8.12 (br s, 1H), 7.33-7.20 (m, 3H), 7.07-7.02 (m, 2H), 4.21 (t, *J* = 4.2 Hz, 1H), 3.84 (ddd, *J* = 13.4, 9.2, 6.3 Hz, 1H), 3.64 (qd, *J* = 6.9 Hz, 2.8 Hz, 1H), 3.17 (dd, *J* = 13.9, 4.8 Hz, 1H, AB system), 3.08 (dd, *J* = 13.9 Hz, 3.6 Hz, 1H, AB system), 2.90 (ddd, *J* = 13.4, 9.0, 5.5 Hz, 1H), 1.67-1.44 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H), 0.26 (d, *J* = 7.1 Hz, 3H); ¹³C NMR (100 MHz, DMSO-*d*₆) δ 166.1, 165.2, 135.6, 130.2, 128.3, 126.9, 59.8, 50.0, 44.8, 36.2, 20.0, 19.5, 11.1; HRMS (ESI-TOF) calcd for C₁₅H₂₁N₂O₂ (M+H)⁺ 261.15975, found 261.15949.

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3 **Solubility.** Thermodynamic solubility was measured by dissolving compounds **4** or **7** up to
4 saturation in a pH 7.4 phosphate-buffered saline (PBS) with the following composition: 137.5
5 mM NaCl, 2.7 mM KCl, 4.3 mM Na₂HPO₄, and 1.4 mM KH₂PO₄. Samples were shaken for
6 24 h at 20 °C. Saturation was confirmed by the presence of undissolved powder. After
7 ultracentrifugation, the concentration in the supernatant was measured by an HPLC procedure
8 using a calibration curve established for each compound by diluting a 10 mM DMSO stock
9 solution to adapted concentrations.
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20 **Stability in mouse plasma.** Stability was determined in mouse plasma at 37 °C after 6 h. For
21 each compound, the 10 mM DMSO stock solution was diluted in MeCN to a final
22 concentration of 100 μM. This solution was again diluted in plasma to a final concentration of
23 1 μM. The mixture was divided into two aliquots. The incubation of each aliquot was stopped
24 at *t*₀ and 6 h by adding one volume of ice cold acetonitrile. Samples were stirred for 3 min,
25 sonicated for 3 min, and then centrifuged at 4 °C before HPLC injection. The percentage of
26 remaining test compound relative to *t*₀ was measured by monitoring the peak area on the
27 chromatogram.
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40 **Microsomal stability in mouse hepatocytes.** Microsomal stability was determined in mouse
41 hepatocytes at 37 °C after 30 min. For each compound, the 10 mM DMSO stock solution was
42 diluted in DMSO to a final concentration of 100 μM. This solution was again diluted to a final
43 concentration of 1 μM in pH 7.4 phosphate-buffered saline (PBS) containing mouse liver
44 microsomes (0.5 mg/mL), 1 mM of NaDPH, and 3 mM of MgCl₂. The mixture was divided
45 into two aliquots. The incubation of each aliquot was stopped at *t*₀ and 30 min by adding one
46 volume of ice-cold acetonitrile. Samples were stirred for 3 min, sonicated for 3 min, and then
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3 centrifuged at 4 °C before HPLC injection. The percentage of remaining test compound
4
5 relative to t_0 was measured by monitoring the peak area on the chromatogram.
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8 9 **ACKNOWLEDGMENTS**

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14
15 analyses (Service Commun d'Analyse, Unistra).
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20 21 **SUPPORTING INFORMATION**

22 ^1H NMR and ^{13}C NMR spectra for all compounds, X-ray crystal structures and
23
24 crystallographic data for **4** and **7**. This material is available free of charge via the Internet at
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26 <http://pubs.acs.org/>.
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REFERENCES

- (1) Kodadek, T. *Chem. Commun.* **2011**, 47, 9757–9763.
- (2) Swinney, D. C.; Anthony, J. *Nat. Rev. Drug Discovery* **2011**, 10, 507–519.
- (3) Ishikawa, M.; Hashimoto, Y. *J. Med. Chem.* **2011**, 54, 1539–1554.
- (4) Agrafiotis, D. K.; Ley, S. V.; Larhed, M.; Khosla, C.; Liu, D. R.; Ganesan, A.; Richardson, R.; Knolle, J.; Hummel, G. G.; Harris, C. J.; Mathis, G.; Trinquet, E.; Schnitzer, R.; Kessler, H.; Lam, K. S.; Bolger, M. B.; Garyantes, T. K.; Banks, M.; Zhang, L.; Reineke, V.; Reimer, V.; Nilsson, P.; Olofsson, K.; Li, J.; Fattinger, C.; Dernick, G.; Ladlow, M.; Vickerstaffe, E.; Tang, Y.; Gibbs, A. C.; Tommasi, R.; Cornella, I.; Klages, J.; Coles, M.; Kumaresan, P. R.; Houston, J. G.; Fraczkiwicz, R.; Steere, B. S.; Casano, F.; Li, Z.; Sommergruber, W.; Kumaresan, P. R. *Exploiting Chemical Diversity for Drug Discovery*; Bartlett, P. A., Entzeroth, M., Eds.; RSC Biomolecular Sciences; The Royal Society of Chemistry, **2006**.
- (5) Huigens III, R. W.; Morrison, K. C.; Hicklin, R. W.; Flood Jr, T. A.; Richter, M. F.; Hergenrother, P. J. *Nat. Chem.* **2013**, 5, 195–202.
- (6) Lovering, F.; Bikker, J.; Humblet, C. *J. Med. Chem.* **2009**, 52, 6752–6756.
- (7) Sun, H.; Tawa, G.; Wallqvist, A. *Drug Discov. Today* **2012**, 17, 310–324.
- (8) Borthwick, A. D. *Chem. Rev.* **2012**, 112, 3641–3716.
- (9) (a) Hoffman, R.; Nayyar, N. *J. Org. Chem.* **1995**, 60, 5992–5994. (b) Hoffman, R. V.; Reddy, M. M.; Klumas, C. M.; Cervantes-Lee, F. *J. Org. Chem.* **1998**, 63, 9128–9130.
- (10) Obreza, A.; Urleb, U. *Synth. Commun.* **2003**, 33, 1011–1018.
- (11) Bourguet, C.B.; Sabatino, D.; Proulx, C.; Klocek, S.; Lubell, W.D. *J. Peptide Sci.* **2010**, 16, 284–296.
- (12) Ivanovich, R. A.; Vincent-Rocan, J.-F.; Elkaeed, E. B.; Beauchemin, A. M. *Org. Lett.* **2015**, 17, 4898–4901
- (13) Bonnet, D.; Margathe, J.-F.; Radford, S.; Pflimlin, E.; Riché, S.; Doman, P.; Hibert, M.; Ganesan, A. *ACS Comb. Sci.* **2012**, 14, 323–334.
- (14) (a) Regenass, P.; Margathe, J.-F.; Mann, A.; Suffert, J.; Hibert, M.; Girard, N.; Bonnet, D. *Chem. Commun.* **2014**, 50, 9657–9660. (b) Regenass, P.; Riché, S.; Peron, F.; Rognan, D.; Hibert, M.; Girard, N.; Bonnet, D. *Org. Biomol. Chem.* **2016**, 14, 8859–8863.
- (15) (a) Fukuyama, T.; Jow, C. K.; Cheung, M. *Tetrahedron Lett.* **1997**, 38, 5831–5834. (b) Kan, T.; Fukuyama, T. *Chem. Commun.* **2004**, 4, 353–359.
- (16) Sun, D.; Zhang, L.; Wang, J. *Asian J. Chem.* **2012**, 24, 319–322.

- 1
2
3 (17) Ryakhovsky, V. V.; Ivanov, A. S. *Tetrahedron*, **2012**, *68*, 7070-7076.
4
5 (18) CCDC 1520133 and 1520134 for **4** and **7**, respectively; please see the Supporting
6 Information.
7
8 (19) Didierjean, C.; Duca, V. D.; Benedetti, E.; Aubry, A.; Zouikri, M.; Marraud, M.;
9 Boussard, G. *J. Pept. Res.* **1997**, *50*, 451–457.
10
11 (20) Malavašič, Č.; Grošelj, U.; Golobič, A.; Bezenšek, J.; Stanovnik, B.; Stare, K.; Wagger,
12 J.; Svete, J. *Tetrahedron: Asymmetry* **2011**, *22*, 629–640.
13
14 (21) Klebe, G. *Nat. Rev. Drug Discovery* **2015**, *14*, 95–110.
15
16 (22) Bouayad-Gervais, S.H and Lubell, W.D. *Molecules* **2013**, *18*, 14739-14746
17
18 (23) Lipinski, C. A.; Lombardo, F.; Dominy, B. W.; Feeney, P. J. *Adv. Drug Deliver. Rev.*
19 **2001**, *46*, 3–26.
20
21
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