

HETEROCYCLES, Vol. 103, No. 1, 2021, pp. 511 - 525. © 2021 The Japan Institute of Heterocyclic Chemistry
Received, 11th September, 2020, Accepted, 21st October, 2020, Published online, 9th November, 2020
DOI: 10.3987/COM-20-S(K)35

DESIGN, SYNTHESIS, PHYSICAL PROPERTIES AND INDOLEAMINE 2, 3-DIOXYGENASE 1 INHIBITORY ACTIVITY OF SUBSTITUED INDOLE DERIVATIVES WITH *N*-H, *N*-METOXYMETHYL, OR *N*-MEHYLTHIOMETHYL GROUPS TOWARD FRAGMENT-BASED DRUG DISCOVERY[§]

Kenta Hayami,^{1#} Yuichi Kuboki,^{1#} Katsumi Ohta,² Bangzhong Lin,¹ Megumi Fumimoto,¹ Kazuto Nunomura,¹ Jun-ichi Haruta,¹ Kenichi Murai,¹ Hiromichi Fujioka,¹ Akira Asai,² and Mitsuhiro Arisawa^{1*}

¹Graduate School of Pharmaceutical Sciences, Osaka University, 1-6 Yamada-oka, Suita, Osaka, Japan. ²Graduate School of Pharmaceutical Sciences, University of Shizuoka, 52-1 Yada, Suruga-ku, Shizuoka, Japan.

E-mail: arisaw@phs.osaka-u.ac.jp

equal contribution

Abstract – We designed and prepared *N*-H, *N*-CH₂OMe (MOM), and *N*-CH₂SMe (MTM) forms of various substituted indoles, using a docking study, as a small fragment library toward fragment-based drug discovery (FBDD) and evaluated their indoleamine 2, 3-dioxygenase 1 (IDO1) inhibitory activities and physical properties.

Indoleamine 2, 3-dioxygenase 1 (IDO1), a well-characterized immunosuppressive enzyme, has attracted growing attention as a potential target for cancer immunotherapy.¹ However, current literature indicates that we are far from understanding the biological relevance of IDO1 expression during tumorigenesis.² Further, 1-methyl-D-tryptophan (also known as indoximod or NLG8189), epacadostat (also known as INCB24360), NLG919 (also known as GDC-0919), and F001287 have entered clinical development (Figure 1).³ However, the failure of clinical trials of several IDO1 inhibitors, including INCB24360, NLG919, and F001287, has been known since the winter of 2017. Thus, discovery of new IDO1 inhibition strategies is extremely urgent.

Some IDO1 inhibitors reported thus far have indole or indole-like structures (Figure 1). In general, the indole scaffold is widely distributed in natural products and bioactive molecules. In view of its unique

physico-chemical and biological properties, it has been used as a privileged scaffold in medicinal chemistry. To date, many natural and synthetic indole derivatives have been discovered as promising agents used in clinical evaluations. On the other hand, current research has not yet reported the effect of *N*-CH₂OMe (MOM) or *N*-CH₂SMe (MTM) substituents on the 1-position nitrogen of poly-substituted indoles on IDO1 inhibitory activity.

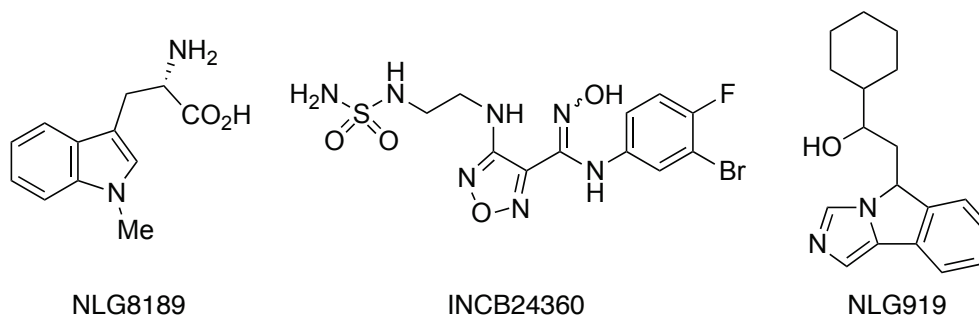
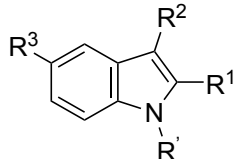


Figure 1. Reported IDO1 inhibitors

Therefore, we prepared *N*-H, *N*-MOM, and *N*-MTM forms of various substituted indoles as a small fragment library toward fragment-based drug discovery (FBDD)⁴ and evaluated their IDO1 inhibitory activities and physical properties. In addition, the docking score between each indole derivative obtained and IDO1 was determined by computational chemistry. The correlation between this docking score and IDO1 inhibitory activity was analyzed to design new molecules, which were also synthesized to evaluate their IDO1 inhibitory activities and physical properties.

First, *N*-MOM and *N*-MTM forms of 2-methylindole and 2-phenylindole were synthesized using standard *N*-alkylation conditions of indole derivatives (Table 1). IDO1 inhibitory activity, solubility, and artificial membrane permeability tests (PAMPA) of these synthesized compounds (including the starting material with the NH moiety) were evaluated (Table 2). An IDO1 cell-based assay, kynurenine production, showed the ratio of tryptophan converted to kynurenine by IDO1. Smaller percentages of kynurenine production indicate higher IDO1 inhibitory activity. Solubility describes the solubility in the second fluid for dissolution test, with higher values indicating higher solubility. The 2-methylindole derivative showed almost no IDO1 inhibition (runs 1–3), whereas the *N*-H, *N*-MOM, and *N*-MTM forms of 2-phenylindole showed kynurenine production rates (runs 4–6) of 31, 44, and 27%, respectively, where the kynurenine production rate is an index of IDO1 inhibitory activity. Compound **1f** showed the highest IDO1 inhibitory activity, though almost insoluble in this solubility experiment (run 6).

Table 3. IDO1 inhibitory activity and physical properties of compounds **1g** – **1s**

run						IDO cell based assay (50 μM)	solubility (μM)	PAMPA (X 10 ⁻⁶ cm/sec)	Glide docking score (kcal/mol)
		R ¹ =	R ² =	R ³ =	R ⁴ =	Kynurenine production (%)			
1	1g	C ₆ H ₄ -pF	H	H	H	50	3.1	11.5	-6.099
2	1h	C ₆ H ₄ -pF	H	H	MOM	27	5.5	2.6	-6.139
3	1i	C ₆ H ₄ -pF	H	H	MTM	31	0.8	0	-6.016
4	1j	C ₆ H ₄ -pMe	H	H	H	63	1.1	1.7	-6.009
5	1k	C ₆ H ₄ -pMe	H	H	MOM	19	1.9	0	-5.883
6	1l	C ₆ H ₄ -pMe	H	H	MTM	18	<0.5	0	-5.55
7	1m	C ₆ H ₄ -pOMe	H	H	H	111	<0.5	2.6	-6.13
8	1n	C ₆ H ₄ -pOMe	H	H	MOM	14	3.2	4.2	-5.556
9	1o	C ₆ H ₄ -pOMe	H	H	MTM	21	<0.5	0	-5.059
10	1p	Ph	CO ₂ Me	H	MOM	11	20	25.4	-5.987
11	1q	Ph	CO ₂ Me	H	MTM	11	2	5.2	-5.316
12	1r	Ph	H	CO ₂ Me	MOM	51	0.7	3.9	-6.032
13	1s	Ph	H	CO ₂ Me	MTM	22	<0.5	0.4	-5.526

Considering biological activity, focusing on the phenyl group at the 2-position, the biological activity of the *N*-MOM and *N*-MTM derivatives tends to improve as the aromatic ring becomes electron-rich. On the other hand, the opposite tendency is seen in the *N*-H derivative. Interestingly, the activity of the 2-phenyl compound with a methoxycarbonyl group at the 3-position instead of the 5-position was improved (runs 1–13). Regarding solubility and PAMPA, the MOM form tended to yield better results than the MTM form, and the MOM group was found to be suitable as a substituent at the indole 1-position.

Next, we designed indole derivatives, **1t–1ab**, having polar substituents at the 5-position, such as OH, CN, and CH₂OH, as the indole derivatives in Table 3 exhibited poor solubility.

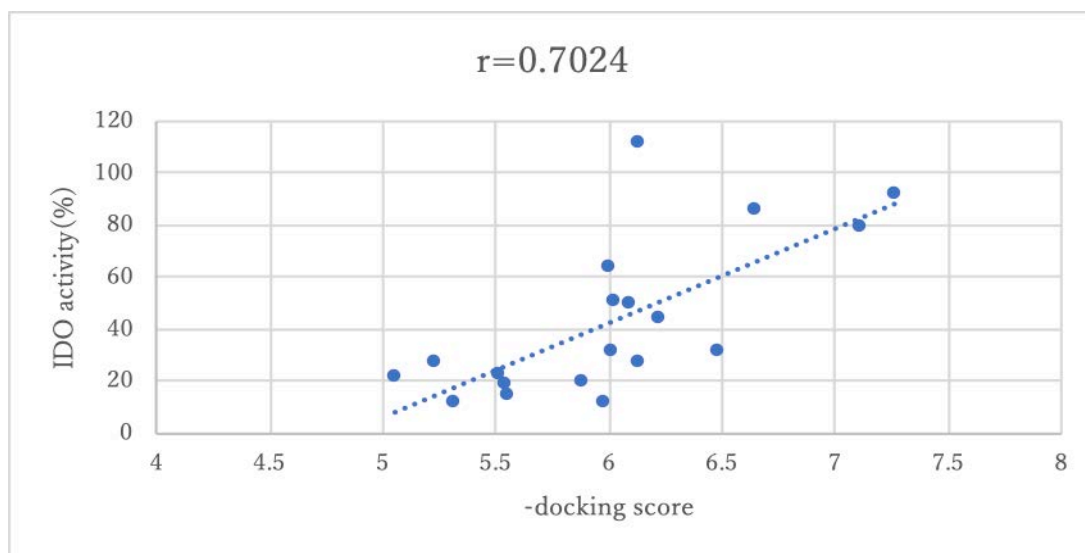
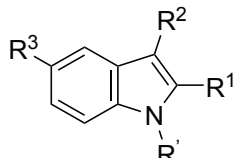


Figure 2. Correlation between docking score and IDO1 activity (%) of indole derivatives in Tables 2 and 3

Furthermore, we proceeded to design and synthesize new compounds by computational chemistry using the previously introduced data. Specifically, using docking software Glide,⁵ we calculated docking scores⁶ of the newly synthesized indole derivatives (Tables 2 and 3) and IDO1 and created a database to show the correlation between docking score and IDO1 inhibitory activities. As a result (Figure 2), the correlation coefficient (r) between the biological activity of the evaluated compound and the docking score⁷ was good (0.7024). From the graph, the activity is predicted to increase as the docking score decreases, and compounds with a docking scores of 5 or less have high activity. We calculated the same docking score of various substituted indoles and found that the indole having a phenyl group at the 2-position and ethoxycarbonyl group at the 3-position and the compound having an ethyl group at the 2-position and methoxycarbonyl group at the 3-position showed the desired docking scores (molecular design), so we prepared these indole derivatives (**1ac–1ah**). In Table 4, we summarize chemical structures of our designed compounds (**1t–1ah**) and their IDO1 inhibitory activities and physical properties.

Table 4. IDO1 inhibitory activity and physical properties of compounds **1t – 1ah**

run						IDO cell based assay (50 μ M)	solubility (μ M)	PAMPA (X 10^{-6} cm/sec)	Glide docking score (kcal/mol)
		R ¹ =	R ² =	R ³ =	R' =	Kynurenine production (%)			
1	1t	H	H	OH	H	107	-	-	-7.506
2	1u	H	H	OH	MOM	112	>95	23.1	-6.054
3	1v	H	H	OH	MTM	118	>95	32.4	-5.232
4	1w	H	H	CN	H	106	94	39.4	-6.505
5	1x	H	H	CN	MOM	104	95	53.3	-5.518
6	1y	H	H	CN	MTM	72	73	49.5	-5.284
7	1z	H	H	CH ₂ OH	H	107	>95	4.4	-7.536
8	1aa	H	H	CH ₂ OH	MOM	110	>95	28.8	-5.921
9	1ab	H	H	CH ₂ OH	MTM	107	>95	34.2	-6.551
10	1ac	Ph	CO ₂ Et	H	H	32	1.9	-	-4.446
11	1ad	Ph	CO ₂ Et	H	MOM	40	1.1	-	-4.428
12	1ae	Ph	CO ₂ Et	H	MTM	-2	6	-	-4.587
13	1af	Et	CO ₂ Me	H	H	14	81	37.3	-4.659
14	1ag	Et	CO ₂ Me	H	MOM	53	43.2	-	-4.815
15	1ah	Et	CO ₂ Me	H	MTM	82	<0.5	-	-5.075

Derivatives (**1t–1ab**) with polar functional groups showed good solubility and PAMPA values but had little IDO1 inhibitory activity, as predicted by docking scores. On the other hand, indole derivatives **1ac–1ah** exhibited IDO1 inhibitory activity, as expected from the docking scores. Figure 3 indicates the relationship between biological activity of the indole compound in Table 4 and the docking score. The correlation coefficient was good (0.74).

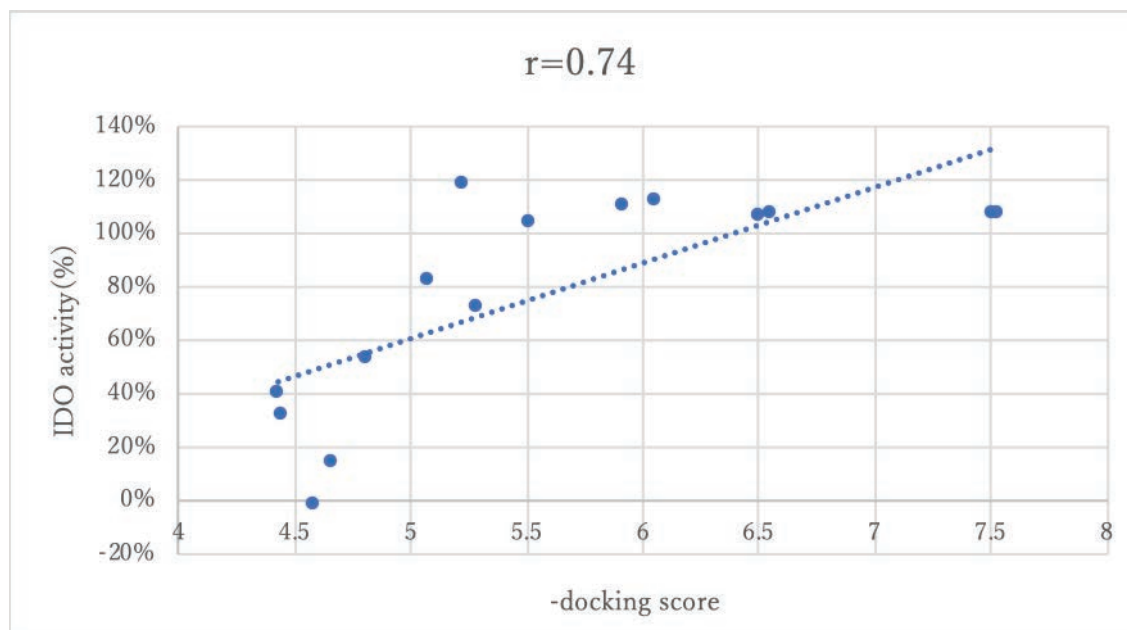


Figure 3. Correlation between docking score and IDO1 activity(%) of indole derivatives in Table 4

In this study, the indole compounds showing satisfactory values for IDO1 inhibitory activity, solubility, and PAMPA were determined to be **1p** and **1af**.⁸ Regarding solubility and PAMPA, the MOM form tended to yield better results than the MTM form, and the MOM group was suitable as a 1-position indole substituent. We believe the results of these studies are useful, not only for the development of IDO1 inhibitors, but also for molecular design using computational chemistry and substituents at the 1-position of indole.

EXPERIMENTAL

Chemistry

• General Information

All reagents were purchased from commercial sources and used without further purification, unless otherwise noted. Reactions were performed under a nitrogen atmosphere using purchased anhydrous solvent. All reactions were monitored by thin-layer chromatography (TLC) using Merck silica gel 60F₂₅₄ (0.25 mm). The products were purified by column chromatography over silica gel Kieselgel 60 (60-210 μm , spherical neutral) purchased from Kanto Chemical or Silica Gel 60N (40-50 μm , spherical neutral) purchased from Kanto Chemical. ¹H, ¹³C and ¹⁹F NMR spectra were recorded at 25 °C on a JEOL JNM-AL300 (at 300 MHz, 75 MHz and 282 MHz respectively), a JEOL JNM-ECS 400 (at 400 MHz, 100 MHz and 376 MHz, respectively) or a JEOL JNM-LA 500 (at 500 MHz, 125 MHz and 470 MHz, respectively), and the chemical shifts are reported relative to an internal standard, tetramethylsilane (TMS) (¹H, δ : = 0.00 ppm), CDCl₃ (¹H, δ : = 7.26 ppm, ¹³C, δ : = 77.0 ppm) or C₆F₆ (¹⁹F, δ : = -162.0 ppm). Data for ¹H NMR spectra are reported as follows: chemical shift (δ : ppm) (multiplicity, coupling constant

(Hz), integration). Multiplicity and qualifier abbreviations are as follows: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet. High-resolution mass spectra (MALDI-TOF) were performed on JEOL JMS-3000. Compounds **1a**, **1d**, **1g**, **1j**, **1m**, **1t**, **1w** and **1z** are commercially available. Compounds **1b**,⁹ **1e**,¹⁰ **1ac**,¹¹ **1af**,¹² Methyl 2-phenyl-1*H*-indole-5-carboxylate¹³ and methyl 2-phenyl-1*H*-indole-3-carboxylate¹³ are known compounds.

• *General procedure for the synthesis of N-MOM or N-MTM indoles*

NaH (1.5 eq.) was added to a solution of indole compounds in DMF at 0 °C. After stirring for 30 min at the same temperature, MOMCl or MTMCl (1.5 eq.) was added dropwise to the solution. The resulting mixture was stirred for 5 h and slowly warmed to room temperature. After removal of the solvent under vacuo. The residue was partitioned between AcOEt and water. The combined organic layers were washed with water and brine, dried over anhydrous Na₂SO₄, filtered, concentrated and purified on silica gel chromatography using *n*-hexane/AcOEt to give the corresponding product.

1-(Methoxymethyl)-2-methyl-1*H*-indole (1b)⁹ Following general procedures, compound **1a** (350 mg, 2.0 mmol) was converted to **1b** (340 mg, 97%) using column eluent (*n*-hexane : AcOEt = 20 : 1). Red oil. ¹H NMR (300 MHz, CDCl₃) δ: 7.40-7.37 (1H, m), 7.22 (1H, d, *J* = 8.3 Hz), 7.06-6.95 (2H, m), 6.14 (1H, s), 5.17 (2H, s), 3.05 (3H, s), 2.28 (3H, s). ¹³C NMR (75 MHz, CDCl₃) δ: 137.44, 136.58, 128.17, 120.96, 119.93, 119.58, 108.95, 101.59, 73.50, 55.37, 12.31.

2-Methyl-1-((methylthio)methyl)-1*H*-indole (1c) Following general procedures, compound **1a** (382 mg, 2.0 mmol) was converted to **1c** (241 mg, 63%) using column eluent (*n*-hexane : AcOEt = 30 : 1). Colorless oil. ¹H MMR (400 MHz, CDCl₃) δ: 7.49 (1H, d, *J* = 7.8 Hz), 7.35 (1H, d, *J* = 8.2 Hz), 7.14 (1H, dd, *J* = 7.1, 3.5 Hz), 7.07 (1H, dd, *J* = 7.3, 3.7 Hz), 6.27 (1H, br s), 5.15 (2H, s), 2.47 (3H, s), 2.01 (3H, s). ¹³C MMR (100 MHz, CDCl₃) δ: 137.0, 136.3, 128.1, 120.8, 119.8, 119.7, 109.3, 101.4, 45.6, 14.1, 12.8. HRMS (MALDI-TOF) calcd for C₁₁H₁₄NS (M+H)⁺: 191.0768, found: 191.0758.

1-(Methoxymethyl)-2-phenyl-1*H*-indole (1e)¹⁰ Following general procedures, compound **1d** (474 mg, 2.0 mmol) was converted to **1e** (470 mg, 99%). using column eluent (*n*-hexane : AcOEt = 30 : 1). Colorless oil. ¹H MMR (400 MHz, CDCl₃) δ: 7.57-7.52 (3H, m), 7.44 (1H, d, *J* = 7.3 Hz), 7.41-7.29 (3H, m), 7.18 (1H, ddd, *J* = 8.2, 1.4, 1.4 Hz), 7.09 (1H, *J* = ddd, *J* = 6.9, 0.9, 0.9 Hz), 6.53 (1H, s), 5.33 (2H, s), 3.21 (3H, s). ¹³C MMR (100 MHz, CDCl₃) δ: 141.8, 138.3, 132.4, 129.5, 128.6, 128.3, 128.1, 122.3, 120.7, 120.6, 110.2, 103.3, 74.7, 55.9.

1-((Methylthio)methyl)-2-phenyl-1*H*-indole (1f) Following general procedures, compound **1d** (507 mg,

2.0 mmol) was converted to **1f** (279 mg, 55%) using column eluent (*n*-hexane : AcOEt = 30 : 1). Colorless oil. ¹H MMR (400 MHz, CDCl₃) δ: 7.56 (1H, d, *J* = 7.8 Hz), 7.49-7.46 (2H, m), 7.43-7.38 (3H, m), 7.35-7.34 (1H, m), 7.19 (1H, dd, *J* = 7.3, 3.7 Hz), 7.10 (1H, dd, *J* = 7.3, 3.7 Hz), 6.48 (1H, s), 5.19 (2H, s), 1.77 (3H, s). ¹³C MMR (100 MHz, CDCl₃) δ: 141.5, 137.4, 132.5, 131.0, 129.6, 128.7, 128.2, 122.0, 120.7, 120.62, 110.8, 103.5, 46.9, 14.6. HRMS (MALDI-TOF) calcd for C₁₆H₁₆NS (M+H)⁺: 253.09252, found: 253.0914

2-(4-Fluorophenyl)-1-(methoxymethyl)-1*H*-indole (1h) Following general procedures, compound **1g** (724 mg, 2.8 mmol) was converted to **1h** (594 mg, 82%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Yellow powder. ¹H NMR (300 MHz, CDCl₃) δ: 7.65-7.61 (m, 3H), 7.50 (d, *J* = 8.2 Hz, 1H), 7.27 (d, *J* = 6.6 Hz, 1H), 7.21-7.14 (m, 3H), 6.59 (s, 1H), 5.40 (s, 2H), 3.34 (s, 3H). ¹³C NMR (125 MHz, CDCl₃) δ: 162.7 (d, *J* = 249 Hz), 140.6, 138.2, 131.2 (d, *J* = 8.8 Hz), 128.4, 128.1, 122.4, 120.8, 120.5, 115.6 (d, *J* = 21.3 Hz), 110.0, 103.4, 74.5, 56.0. ¹⁹F NMR (CDCl₃, 375 MHz) δ: -113.7. HRMS (MALDI-TOF) calcd for C₁₆H₁₄FNO (M)⁺: 255.10592, found: 255.10574. mp 57-58 °C (*n*-hexane /AcOEt).

2-(4-Fluorophenyl)-1-((methylthio)methyl)-1*H*-indole (1i) Following general procedures, compound **1g** (1.18 g, 4.4 mmol) was converted to **1i** (531 mg, 45%) using column eluent (*n*-hexane : AcOEt = 30 : 1). Pale red powder. ¹H NMR (400 MHz, CDCl₃) δ: 7.70 (d, *J* = 7.8 Hz, 1H), 7.63-7.56 (m, 3H), 7.33 (dd, *J* = 8.9 Hz, 1H), 7.24 (m, 3H), 6.61 (s, 1H), 5.30 (s, 2H), 1.96 (s, 3H). ¹³C NMR (125 MHz, CDCl₃) δ: 162.7 (d, *J* = 238 Hz), 140.2, 137.3, 131.4 (d, *J* = 12.5 Hz), 128.6, 128.5, 128.3, 122.1, 120.6, 115.7 (d, *J* = 25 Hz), 110.7, 103.6, 46.8, 14.7. ¹⁹F NMR (CDCl₃, 375 MHz) δ: -113.7. HRMS (MALDI-TOF) calcd for C₁₆H₁₄FNS(M)⁺: 271.08314, found: 271.08327. mp 81-86 °C (*n*-hexane /AcOEt).

1-(Methoxymethyl)-2-(*p*-tolyl)-1*H*-indole (1k) Following general procedures, compound **1j** (382 mg, 1.5 mmol) was converted to **1k** (333 mg, 87%) using column eluent (*n*-hexane : AcOEt = 10 : 1). White powder. ¹H NMR (300 MHz, CDCl₃) δ: 7.60 (d, *J* = 7.8 Hz, 1H), 7.49 (d, *J* = 7.2 Hz, 2H), 7.47-7.46 (m, 1H), 7.23 (d, *J* = 7.2 Hz, 2H), 7.20-7.16 (m, 1H), 7.13 (dd, *J* = 7.3, 7.3 Hz, 1H), 6.55 (s, 1H), 5.39 (s, 2H), 3.26 (s, 3H), 2.39 (s, 3H). ¹³C NMR (75 MHz, CDCl₃) δ: 141.8, 138.1, 138.0, 129.4, 129.3, 129.2, 128.3, 122.1, 120.6, 120.4, 110.1, 102.9, 74.6, 55.8, 21.2. HRMS (MALDI-TOF) calcd for C₁₇H₁₇NO(M)⁺: 251.13104, found: 251.13122. mp 60-61 °C (*n*-hexane /AcOEt).

1-((Methylthio)methyl)-2-(*p*-tolyl)-1*H*-indole (1l) Following general procedures, compound **1j** (418 mg, 1.5 mmol) was converted to **1l** (180 mg, 43%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Pale red powder. ¹H NMR (400 MHz, CDCl₃) δ: 7.62 (d, *J* = 7.8 Hz, 1H), 7.49 (d, *J* = 7.9 Hz, 1H), 7.29 (d, *J* = 8.8

Hz, 2H), 7.24 (m, $J = 8.0$ Hz, 3H), 7.17 (dd, $J = 7.6, 7.6$ Hz, 1H), 6.52 (s, 1H), 5.26 (s, 2H), 2.43 (s, 3H), 1.85 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ : 141.5, 138.1, 137.2, 129.53, 129.51, 129.3, 128.5, 121.8, 120.58, 120.53, 110.7, 103.1, 46.8, 21.2, 14.6. HRMS (MALDI-TOF) calcd for $\text{C}_{17}\text{H}_{17}\text{NS}(\text{M})^+$: 267.10825, found: 267.10834. mp 60-61 °C (*n*-hexane /AcOEt).

1-(Methoxymethyl)-2-(4-methoxyphenyl)-1*H*-indole (1n) Following general procedures, compound **1m** (382 mg, 1.4 mmol) was converted to **1n** (321 mg, 84%) using column eluent (*n*-hexane : AcOEt = 10 : 1). White powder. ^1H NMR (400 MHz, CDCl_3) δ : 7.62 (d, $J = 7.8$ Hz, 1H), 7.56 (d, $J = 7.6$ Hz, 2H), 7.51 (d, $J = 7.5$ Hz, 1H), 7.25 (dd, $J = 7.4, 7.4$ Hz, 1H), 7.17 (dd, $J = 7.6, 7.6$ Hz, 1H), 7.01 (d, $J = 7.6$ Hz, 2H), 6.56 (s, 1H), 5.41 (s, 2H), 3.87 (s, 3H), 3.31 (s, 3H). ^{13}C NMR (75 MHz, CDCl_3) δ : 159.6, 141.6, 138.1, 130.7, 128.3, 124.7, 122.0, 120.6, 120.3, 114.0, 110.0, 102.6, 74.6, 55.9, 55.3. HRMS (MALDI-TOF) calcd for $\text{C}_{17}\text{H}_{17}\text{NO}_2(\text{M})^+$: 267.12592, found: 267.12585. mp 65-66 °C (*n*-hexane /AcOEt).

2-(4-Methoxyphenyl)-1-((methylthio)methyl)-1*H*-indole (1o) Following general procedures, compound **1m** (192 mg, 0.7 mmol) was converted to **1o** (73 mg, 38%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Pale red powder. ^1H NMR (400 MHz, CDCl_3) δ : 7.61 (d, $J = 7.2$ Hz, 1H), 7.50-7.47 (m, 3H), 7.22 (d, $J = 7.5$ Hz, 2H), 7.21-7.19 (m, 1H), 7.16-7.11 (m, 1H), 6.55 (s, 1H), 5.39 (s, 2H), 3.29 (s, 3H), 2.40 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ : 141.5, 138.2, 137.2, 129.53, 129.51, 129.3, 128.7, 121.8, 120.6, 120.5, 103.1, 55.3, 46.8, 21.2, 14.6. HRMS (MALDI-TOF) calcd for $\text{C}_{17}\text{H}_{17}\text{NOS}(\text{M})^+$: 283.10314, found: 283.10327. mp 80-81 °C (*n*-hexane /AcOEt).

Methyl 1-(methoxymethyl)-2-phenyl-1*H*-indole-3-carboxylate (1p) Following general procedures, methyl 2-phenyl-1*H*-indole-3-carboxylate (155 mg, 0.5 mmol)¹¹ was converted to **1p** (120 mg, 77%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Orange oil. ^1H NMR (300 MHz, CDCl_3) δ : 8.23-8.19 (m, 1H), 7.55-7.52 (m, 1H), 7.49-7.41 (m, 5H), 7.34-7.30 (m, 2H), 5.26 (s, 2H), 3.74 (s, 3H), 3.14 (s, 3H). ^{13}C NMR (100 MHz, CDCl_3) δ : 165.5, 146.9, 136.4, 130.8, 130.5, 129.1, 128.0, 126.6, 123.4, 122.6, 122.0, 110.6, 106.5, 74.6, 56.0, 50.8. HRMS (MALDI-TOF) calcd for $\text{C}_{18}\text{H}_{17}\text{NO}_3(\text{M})^+$: 295.12085, found: 295.12077.

Methyl 1-((methylthio)methyl)-2-phenyl-1*H*-indole-3-carboxylate (1q) Following general procedures, methyl 2-phenyl-1*H*-indole-3-carboxylate (329 mg, 1.0 mmol)¹¹ was converted to **1q** (135 mg, 41%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Orange oil. ^1H NMR (300 MHz, CDCl_3) δ : 8.24-8.19 (m, 1H), 7.54-7.45 (m, 4H), 7.44-7.41 (m, 2H), 7.36-7.30 (m, 2H), 5.05 (s, 2H), 3.73 (s, 3H), 1.86 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3) δ : 165.3, 146.5, 135.8, 130.8, 130.7, 129.2, 128.1, 126.8, 123.1, 122.6,

122.1, 111.0, 106.3, 50.8, 46.8, 14.9. HRMS (MALDI-TOF) calcd for $C_{18}H_{17}NO_2S(M)^+$: 311.09807, found: 311.09824.

Methyl 1-(methoxymethyl)-2-phenyl-1H-indole-5-carboxylate (1r) Following general procedures, methyl 2-phenyl-1H-indole-5-carboxylate (139 mg, 0.5 mmol)¹¹ was converted to **1r** (104 mg, 75%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Beige powder. ¹H NMR (300 MHz, CDCl₃) δ: 8.32-8.31 (m, 1H), 7.92-7.88 (m, 1H), 7.56-7.53 (m, 2H), 7.47-7.38 (m, 4H), 6.61 (s, 1H), 5.36 (s, 2H), 3.87 (s, 3H), 3.23 (s, 3H). ¹³C NMR (75 MHz, CDCl₃) δ: 168.0, 143.2, 140.7, 131.8, 129.5, 128.7, 128.5, 128.0, 123.7, 123.4, 122.8, 110.0, 104.3, 74.8, 56.1, 51.9. HRMS (MALDI-TOF) calcd for $C_{18}H_{17}NO_3(M)^+$: 295.1208, found: 295.1219. mp 78-79 °C (*n*-hexane /AcOEt).

Methyl 1-((methylthio)methyl)-2-phenyl-1H-indole-5-carboxylate (1s) Following general procedures, methyl 2-phenyl-1H-indole-5-carboxylate (780 mg, 2.5 mmol)¹¹ was converted to **1s** (312 mg, 40%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Orange oil. ¹H NMR (400 MHz, CDCl₃) δ: 8.32-8.31 (m, 1H), 7.91-7.89 (m, 1H), 7.50-7.37 (m, 6H), 6.57 (s, 1H), 5.20 (s, 2H), 3.88 (s, 3H), 1.79 (s, 3H). ¹³C NMR (125 MHz, CDCl₃) δ: 168.1, 142.8, 140.0, 131.9, 129.7, 128.8, 128.6, 128.1, 123.5, 123.3, 122.6, 110.5, 104.5, 51.9, 47.0, 14.7. HRMS (MALDI-TOF) :calcd for $C_{18}H_{17}NO_2S(M)^+$: 311.09804, found: 311.09821.

1-(Methoxymethyl)-1H-indol-5-ol (1u) Following general procedures, compound **1t** (48 mg, 0.3 mmol) was converted to **1u** (40 mg, 84%) using column eluent (*n*-hexane : AcOEt = 5 : 1). Brown powder. ¹H NMR (300 MHz, CDCl₃) δ: 7.15 (d, *J* = 8.7 Hz, 1H), 6.95 (d, *J* = 3.6 Hz, 1H), 6.84(d, *J* = 2.4 Hz, 1H), 6.62 (d, *J* = 2.4 Hz, 1H), 6.22 (d, *J* = 3.3 Hz, 1H), 5.21 (s, 2H), 3.04 (s, 3H). ¹³C NMR (100 MHz, CDCl₃) δ: 149.9, 131.7, 129.9, 129.1, 111.8, 110.5, 105.4, 101.8, 76.7, 55.8. HRMS (MALDI-TOF) calcd for $C_{10}H_{11}NO_2(M+H)^+$: 177.07830, found: 177.07843. mp 48-50 °C (*n*-hexane /AcOEt).

1-((Methylthio)methyl)-1H-indol-5-ol (1v) Following general procedures, compound **1t** (115 mg, 0.6 mmol) was converted to **1v** (47 mg, 41%) using column eluent (*n*-hexane : AcOEt = 5 : 1). Brown oil. ¹H NMR (300 MHz, CD₃OD) δ: 8.77 (s, 1H), 7.33 (d, *J* = 3.0 Hz, 2H), 6.86 (d, *J* = 2.4 Hz, 1H), 6.66 (dd, *J* = 8.9, 2.4 Hz, 1H), 5.30 (s, 2H), 1.97 (s, 3H). ¹³C NMR (75 MHz, CD₃OD) δ: 152.0, 130.8, 130.3, 130.1, 112.2, 111.8, 105.3, 101.2, 49.5, 14.9. HRMS (MALDI-TOF) calcd for $C_{10}H_{11}NOS(M+H)^+$: 194.06318, found: 194.06341.

1-(Methoxymethyl)-1H-indole-5-carbonitrile (1x) Following general procedures, compound **1w** (803

mg, 4.3 mmol) was converted to **1x** (651 mg, 81%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Brown oil. ¹H NMR (300 MHz, CDCl₃) δ: 7.97 (s, 1H), 7.54 (d, *J* = 8.4 Hz, 1H), 7.47 (d, *J* = 8.2 Hz, 1H), 7.30 (d, *J* = 3.0 Hz, 1H), 6.61 (d, *J* = 3.0 Hz, 1H), 5.47 (s, 2H), 3.24 (s, 3H). ¹³C NMR (75 MHz, CDCl₃) δ: 137.8, 130.2, 128.8, 126.4, 125.1, 120.5, 110.8, 103.4, 103.3, 76.6, 56.0. HRMS (MALDI-TOF) calcd for C₁₁H₁₁N₂O (M)⁺: 187.08660, found : 187.08659.

1-((Methylthio)methyl)-1*H*-indole-5-carbonitrile (1y) Following general procedures, compound **1w** (1.41 g, 7.0 mmol) was converted to **1y** (537 mg, 38%) using column eluent (*n*-hexane : AcOEt = 10 : 1). Orange powder. ¹H NMR (300 MHz, CDCl₃) δ: 7.96 (s, 1H), 7.46-7.45 (m, 2H), 7.30 (d, *J* = 3.0 Hz, 1H), 6.59 (d, *J* = 3.3 Hz, 1H), 5.16 (s, 2H), 1.98 (s, 3H). ¹³C NMR (100 MHz, CDCl₃) δ: 137.4, 130.0, 128.8, 126.6, 124.8, 120.5, 110.7, 103.21, 103.19, 49.6, 14.5. HRMS (MALDI-TOF) calcd for C₁₁H₁₁N₂S (M)⁺: 203.06353, found: 203.06357. mp 54-55 °C (*n*-hexane /AcOEt).

(1-(Methoxymethyl)-1*H*-indol-5-yl)-methanol (1aa) Following general procedures, compound **1z** (147 mg, 0.8 mmol) was converted to **1aa** (122 mg, 83%) using column eluent (*n*-hexane : AcOEt = 5 : 1). Brown oil. ¹H NMR (300 MHz, CDCl₃) δ: 7.61 (s, 1H), 7.47 (d, *J* = 8.4 Hz, 1H), 7.27 (d, *J* = 2.9 Hz, 1H), 7.18 (d, *J* = 3.3 Hz, 1H), 6.52 (dd, *J* = 3.5, 1.0 Hz, 1H), 5.44 (s, 2H), 4.76 (s, 2H), 3.21 (s, 3H). ¹³C NMR (100 MHz, CDCl₃) δ: 135.9, 132.9, 129.1, 128.6, 122.0, 119.8, 110.0, 102.6, 76.7, 66.1, 55.8. HRMS (MALDI-TOF) calcd for C₁₁H₁₃NO₂(M)⁺: 191.09421, found: 191.09408.

(1-((Methylthio)methyl)-1*H*-indol-5-yl)-methanol (1ab) Following general procedures, compound **1z** (327 mg, 1.5 mmol) was converted to **1aa** (121 mg, 37%) using column eluent (*n*-hexane : AcOEt = 5 : 1). Brown powder. ¹H NMR (300 MHz, CDCl₃) δ: 7.60 (s, 1H), 7.42 (d, *J* = 8.7 Hz, 1H), 7.27 (d, *J* = 8.7 Hz, 1H), 7.19 (d, *J* = 3.0 Hz, 1H), 6.50 (d, *J* = 3.6 Hz, 1H), 5.16 (s, 2H), 4.75 (s, 2H), 1.97 (s, 3H). ¹³C NMR (75 MHz CDCl₃) δ: 135.5, 132.7, 129.1, 128.3, 121.8, 120.1, 110.0, 102.4, 66.1, 49.4, 14.4. HRMS (MALDI-TOF) calcd for C₁₁H₁₄NOS (M+H)⁺: 208.07881, found: 208.07906. mp 49-50 °C (*n*-hexane /AcOEt).

Ethyl 1-(methoxymethyl)-2-phenyl-1*H*-indole-3-carboxylate (1ad) Following general procedures, compound **1ac** (246 mg, 0.8 mmol)¹³ was converted to **1ad** (202 mg, 82%) using column eluent (*n*-hexane : AcOEt = 7 : 1). White powder. ¹H NMR (300 MHz, CDCl₃) δ: 8.27-8.24 (m, 1H), 7.56-7.53 (m, 1H), 7.49-7.43 (m, 5H), 7.35-7.25 (m, 2H), 5.28 (s, 2H), 4.19 (q, *J* = 7.5 Hz, 2H), 3.16 (s, 3H), 1.17 (t, *J* = 7.0 Hz, 3H). ¹³C NMR (125 MHz, CDCl₃) δ: 165.0, 146.7, 136.3, 131.0, 130.6, 129.1, 127.9, 126.8, 123.4, 122.6, 122.0, 110.5, 106.7, 74.6, 59.5, 56.0, 14.1. HRMS (MALDI-TOF) calcd for C₁₉H₁₉NO₃

(M)⁺: 309.13648, found: 309.13634. mp 108-109 °C (*n*-hexane /AcOEt).

Ethyl 1-((methylthio)methyl)-2-phenyl-1*H*-indole-3-carboxylate (1ae) Following general procedures, compound **1ac** (278 mg, 0.9 mmol)¹³ was converted to **1ae** (125 mg, 45%) using column eluent (*n*-hexane : AcOEt = 15 : 1). White powder. ¹H NMR (500 MHz, CDCl₃) δ: 8.20-8.19 (m, 1H), 7.47-7.45 (m, 1H), 7.43-7.42 (m, 3H), 7.38-7.36 (m, 2H), 7.28-7.26 (m, 2H), 5.00 (s, 2H), 4.12 (q, *J* = 7.2 Hz, 2H), 1.81 (s, 3H), 1.10 (t, *J* = 6.9 Hz, 3H). ¹³C NMR (125 MHz, CDCl₃) δ: 165.0, 146.3, 135.8, 131.1, 130.7, 129.1, 128.0, 127.0, 123.1, 122.5, 122.1, 110.9, 106.5, 59.4, 46.7, 14.8, 14.1. HRMS (MALDI-TOF) calcd for C₁₉H₁₉NO₂S (M)⁺: 325.11367, found: 325.11354. mp 97-98 °C (*n*-hexane /AcOEt).

Methyl 2-ethyl-1-(methoxymethyl)-1*H*-indole-3-carboxylate (1ag) Following general procedures, compound **1af** (50 mg, 0.2 mmol)¹² was converted to **1ag** (39 mg, 77%) using column eluent (*n*-hexane : AcOEt = 6 : 1). White powder. ¹H NMR (300 MHz, CDCl₃) δ: 8.14-8.11 (m, 1H), 7.46-7.43 (m, 1H), 7.27-7.23 (m, 2H), 5.49 (s, 2H), 3.94 (s, 3H), 3.29 (s, 3H), 3.27 (q, *J* = 7.7 Hz, 2H), 1.29 (t, *J* = 7.7 Hz, 3H). ¹³C NMR (75 MHz, CDCl₃) δ: 166.0, 151.2, 136.5, 126.6, 122.6, 122.1, 121.6, 109.6, 104.3, 73.6, 56.0, 50.8, 18.9, 14.1. HRMS (MALDI-TOF) calcd for C₁₄H₁₇NO₃ (M)⁺: 247.12085, found: 247.12072. mp 58-59 °C (*n*-hexane /AcOEt).

Methyl 2-ethyl-1-((methylthio)methyl)-1*H*-indole-3-carboxylate (1ah) Following general procedures, compound **1af** (40 mg, 0.2 mmol)¹² was converted to **1ah** (17 mg, 43%) using column eluent (*n*-hexane : AcOEt = 8 : 1). Yellow oil. ¹H NMR (400 MHz, CDCl₃) δ: 8.14-8.11 (m, 1H), 7.43-7.40 (m, 1H), 7.27-7.24 (m, 2H), 5.20 (s, 2H), 3.94 (s, 3H), 3.28 (q, *J* = 7.5 Hz, 2H), 2.06 (s, 3H), 1.30 (t, *J* = 7.4 Hz, 3H). ¹³C NMR (100 MHz, CDCl₃) δ: 165.9, 150.6, 136.0, 126.7, 122.3, 122.1, 121.7, 110.0, 104.3, 50.8, 45.4, 19.0, 14.5, 13.9. HRMS (MALDI-TOF) calcd for C₁₄H₁₇NO₂S (M)⁺: 263.09805, found: 263.09822.

Biology

Inhibitory activity for cellular kynurenine production and cell viability

The kynurenine production in A431 cells was determined as follows. In brief, A431 cells (3.0 x 10⁵ cells/mL) were seeded in a 96-well culture plate (100 μL/well) and grown overnight. Serial DMSO dilutions of compounds in a total volume of 100 μL culture medium including tryptophan and human IFN-γ (10 ng/mL final concentration) per well were added into wells containing the cells. After an additional 24 h of incubation, 200 μL/well of a mixed solution of 7% (v/v) aqueous CCl₃CO₂H and 2% (w/v) *p*-dimethylaminobenzaldehyde in acetic acid (2:5) was added into each well. The yellow color derived from kynurenine was measured at 460 nm using a SpectraMax M5 multi-mode microplate reader

(Molecular Devices). The cell viability of A431 cells was assessed using CCK-8 assay. The result of this experiment is the average performed at $n = 3$.

Solubility

Solubility of each compound in the 2nd fluid for dissolution test (pH 6.8), was measured at a final concentration of 100 μM in 1% DMSO. After shaking for 5hr, each solution was filtered using MultiScreen HTS MSSLBPC10 (Millipore) and filtrates were analyzed via HPLC (Waters) with photodiode array detection (wavelength was 280 nm). This is a one-time experiment. However, it is a routine experiment, and it is analyzed together with the control compound every time, and it is confirmed from this result that the experiment is established.

Permeability

Parallel artificial membrane permeability assay was done using GentestTM Pre-coated PAMPA Plate System (CORNING). Procedure was initiated by adding donor solutions, 100 μM in 0.1 M phosphate buffer (pH 6.5) containing 5% DMSO, to each well of the donor plate. The receiver plate was then placed onto the donor plate and phosphate buffer (pH 7.4) containing 5% of DMSO was added to the acceptor well. After 5 h incubation, plates were separated and compounds were analyzed via HPLC (Waters) with photodiode array detection (wavelength was 280 nm). Correlation of permeability coefficients (P_{app}) was calculated according to manufacturer's procedure. This is a one-time experiment. However, it is a routine experiment, and it is analyzed together with the control compound every time, and it is confirmed from this result that the experiment is established.

ACKNOWLEDGEMENTS

This work was partially supported by a Grant-in-Aid from JSPS KAKENHI for Precisely Designed Catalysts with Customized Scaffolding (Grant No. JP 18H04260), T15K149760, and T15KT00630, by Platform Project for Supporting Drug Discovery and Life Science Research (Basis for Supporting Innovative Drug Discovery and Life Science Research (BINDS)) from AMED under Grant Number JP20am0101084 and JP20am0101085 (support number 1974), and by Cooperative Research Program of "Network Joint Research Center for Materials and Devices" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

REFERENCES AND NOTES

[§]This paper is dedicated to Dr. Yasuyuki Kita on the occasion of his 77th birthday.

1. J. R. Moffett and M. A. Namboodiri, *Immunol. Cell Biol.*, 2003, **81**, 247.
2. S. Lob, A. Konigsrainer, H. G. Rammensee, G. Opelz, and P. Ternes, *Nat. Rev.*

- Cancer*, 2009, **9**, 445.
3. (a) E. Vacchelli, F. Aranda, A. Eggermont, C. Sautès-Fridman, E. Tartour, E. P. Kennedy, M. Platten, L. Zitvogel, G. Kroemer, and L. Galluzzi, *Oncoimmunology*, 2014, **3**, e957994; (b) U. F. Rohrig, S. R. Majjigapu, P. Vogel, V. Zoete, and O. Michielin, *J. Med. Chem.*, 2015, **58**, 9421; (c) A. Buque, N. Bloy, F. Aranda, I. Cremer, A. Eggermont, W. H. Fridman, J. Fucikova, J. Galon, R. Spisek, E. Tartour, L. Zitvogel, G. Kroemer, and L. Galluzzi, *Oncoimmunology*, 2016, **5**, e1149674.
 4. G. M. Keserű, D. A. Erlanson, G. G. Ferenczy, M. M. Hann, C. W. Murray, and S. D. Pickett, *J. Med. Chem.*, 2016, **59**, 8189.
 5. (a) Glide, version 8.2, Schrödinger, LLC, New York, NY, 2019; (b) R. A. Friesner, J. L. Banks, R. B. Murphy, T. A. Halgren, J. J. Klicic, D. T. Mainz, M. P. Repasky, E. H. Knoll, D. E. Shaw, M. Shelley, J. K. Perry, P. Francis, and P. S. Shenkin, *J. Med. Chem.*, 2004, **47**, 1739; (c) T. A. Halgren, R. B. Murphy, R. A. Friesner, H. S. Beard, L. L. Frye, W. T. Pollard, and J. L. Banks, *J. Med. Chem.*, 2004, **47**, 1750.
 6. The protein to be used (5XE1 in this study) is taken in from PDB, and the protein is optimized via the Protein preparation wizard. Next, open the receptor grid generation, select the ligand, and execute run. Finally, open ligand docking and perform docking calculations with the ligand. The closer the docking score was to 0, the stronger the inhibitory activity. When we started this research project, there were 44 pdb reports of IDO1 and we evaluated the best pdb for our project, which gave the best correlation coefficient r , should be 5XE1. Structural insights into the binding mechanism of IDO1 with hydroxylamidine based inhibitor INCB14943. Y. Wu, T. Xu, J. Liu, K. Ding, and J. Xu, *Biochem. Biophys. Res. Commun.*, 2017, **487**, 339.
 7. R. A. Friesner, R. B. Murphy, M. P. Repasky, L. L. Frye, J. R. Greenwood, T. A. Halgren, P. C. Sanschagrin, and D. T. Mainz, *J. Med. Chem.*, 2006, **49**, 6177.
 8. Docking model of compound **1af** was shown in Supporting Information, Figure S1.
 9. T. Goto, Y. Natori, K. Takeda, H. Nambu, and S. Hashimoto, *Tetrahedron: Asymmetry*, 2011, **22**, 907.
 10. C.-C. Tseng, G. Baillie, G. Donvito, M. A. Mustafa, S. E. Juola, C. Zanato, C. Massarenti, S. D. Angelo, W. T. A. Harrison, A. H. Lichtman, R. A. Ross, M. Zanda, and I. R. Greig, *J. Med. Chem.*, 2019, **62**, 5049.
 11. L. Ackermann, L. Wang, and A. V. Lygin, *Chem. Sci.*, 2012, **2**, 177.
 12. X. Liu, Z. Li, J. Xie, P. Liu, J. Zhang, and B. Dai, *Tetrahedron*, 2016, **72**, 653.
 13. C. Liu, L. Ding, G. Guo, W. Liu, and F. Yang, *Org. Biomol. Chem.*, 2016, 2824.
 14. J.-M. Hwang, T. Oh, T. Kaneko, A. M. Upton, S. G. Franzblau, Z. Ma, S.-N. Cho, and P. Kim, *J. Nat. Prod.*, 2013, **76**, 354.

15. M. H. Oh, H. J. Lee, S. H. Jo, B. B. Park, S.-B. Park, E.-y. Kim, Y. Zhou, Y. H. Jeon, and K. Lee, *Biol. Pharm. Bull.*, 2017, **40**, 419.