Supporting Information

CycPeptMPDB: A Comprehensive Database of Membrane Permeability of Cyclic Peptides

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1 Supplemental Tables

Table S1: Source literature list for CycPeptMPDB. The number of peptides, molecular weight range, and assay type of membrane permeability for each source are shown.

Source	Peptides	Molecular weight	PAMPA	Caco-2	RRCK	MDCK
2006_Rezai_1 [1]	10	712.9 – 1202.6	√			
2006_Rezai_2 [2]	11	710.9 - 840.1	\checkmark			
2011_White [3]	10	712.9 - 1202.6			\checkmark	
2012_Rand [4]	16	712.9 - 828.1		\checkmark	\checkmark	
2013_CHUGAI [5]	878	813.0 - 1777.7	\checkmark			
2013_Zaretsky [6]	2	471.6 - 627.8		\checkmark		
2014_Nielsen [7]	4	709.9 - 778.0			\checkmark	
2015_Ahlbach [8]	34	414.5 - 1620.7	\checkmark			
2015_Bockus_1 [9]	16	755.0 - 1202.6	\checkmark		\checkmark	
2015_Bockus_2 [10]	17	707.9 - 778.0	\checkmark	\checkmark		
2015_Hewitt [11]	18	712.9 - 755.0		\checkmark		
2015_Lewis [12]	2	712.9 - 755.0	\checkmark			\checkmark
2015_Marelli [13]	10	454.5 - 849.0	\checkmark	\checkmark		
2015_Nielsen [14]	3	724.9 - 785.1	\checkmark			
2015_Schwochert [15]	13	712.9 - 793.0			\checkmark	
2015_Wang [16]	62	454.5 - 882.1	\checkmark	\checkmark		
2016_Fouché [17]	15	790.9 - 1199.6				\checkmark
2016_Frost [18]	12	542.6 - 699.9	\checkmark			
2016_Furukawa [19]	688	606.8 - 944.2	\checkmark	\checkmark		
2016_Hickey [20]	18	662.8 - 1202.6	\checkmark			
2016_Schwochert [21]	8	696.9 - 731.0				\checkmark
2017_Boehm [22]	14	848.1 - 929.1			\checkmark	
2017_Price [23]	2	1019.4 - 1202.6			\checkmark	
2017_Pye [24]	21	785.0 - 1151.5	\checkmark		\checkmark	
2018_Buckton [25]	19	596.7 - 744.8	\checkmark	\checkmark		
2018_CHUGAI [26]	374	1062.3 - 1664.2		\checkmark		
2018_García-Pindado [27]	4	725.9 - 883.7	\checkmark			
2018_Kaneda [28]	7	842.1 - 870.1	\checkmark			
2018_Lee [29]	6	639.7 - 653.7	\checkmark			
2018_Naylor [30]	81	578.8 - 1218.6	\checkmark		\checkmark	
2018_Ramalho [31]	10	767.0 - 851.0	\checkmark	\checkmark		
2019_Ono [32]	8	712.9 - 712.9	\checkmark			
2020_Barlow [33]	26	537.7 - 753.0	\checkmark			
2020_Furukawa [34]	36	987.3 - 1197.5	\checkmark			\checkmark
2020_Hosono [35]	11	712.9 - 727.0	\checkmark			
2020_Le Roux [36]	47	342.4 - 486.7	\checkmark	\checkmark		
2020_Townsend [37]	3086	654.9 - 958.2	\checkmark			
2021_Comeau [38]	42	430.5 - 458.6	\checkmark	\checkmark		
2021_Golosov [39]	27	758.0 - 1076.5	\checkmark		\checkmark	
2021_Kelly [40]	1519	974.3 - 1220.4	\checkmark			\checkmark
2021_Lee [41]	5	1160.6 - 1231.7	\checkmark	\checkmark		
2021_Wang [42]	24	959.2 - 1169.5	\checkmark			
2022_Bhardwaj [43]	136	622.8 - 1299.7	\checkmark	\checkmark		
2022_Lee [44]	24	1160.6 - 1251.7	\checkmark			
2022_Saunders [45]	11	542.6 - 623.7	\checkmark			
2022_Taechalertpaisarn [46]	52	661.8 - 856.1	\checkmark			
2022_Tamura [47]	12	792.0 - 950.2	\checkmark			

References

- [1] Rezai, T., Yu, B., Millhauser, G. L., Jacobson, M. P., and Lokey, R. S. (2006a). Testing the conformational hypothesis of passive membrane permeability using synthetic cyclic peptide diastereomers. *J. Am. Chem. Soc.*, **128**(8), 2510–2511.
- [2] Rezai, T., Bock, J. E., Zhou, M. V., Kalyanaraman, C., Lokey, R. S., and Jacobson, M. P. (2006b). Conformational flexibility, internal hydrogen bonding, and passive membrane permeability: Successful in silico prediction of the relative permeabilities of cyclic peptides. J. Am. Chem. Soc., 128(43), 14073–14080.
- [3] White, T. R., Renzelman, C. M., Rand, A. C., Rezai, T., McEwen, C. M., Gelev, V. M., Turner, R. A., Linington, R. G., Leung, S. S., Kalgutkar, A. S., Bauman, J. N., Zhang, Y., Liras, S., Price, D. A., Mathiowetz, A. M., Jacobson, M. P., and Lokey, R. S. (2011). Onresin N-methylation of cyclic peptides for discovery of orally bioavailable scaffolds. *Nat. Chem. Biol.*, 7(11), 810–817.
- [4] Rand, A. C., Leung, S. S. F., Eng, H., Rotter, C. J., Sharma, R., Kalgutkar, A. S., Zhang, Y., Varma, M. V., Farley, K. A., Khunte, B., Limberakis, C., Price, D. A., Liras, S., Mathiowetz, A. M., Jacobson, M. P., and Lokey, R. S. (2012). Optimizing PK properties of cyclic peptides: the effect of side chain substitutions on permeability and clearance. *MedChemComm*, 3(10), 1282–1289.
- [5] Chugai Pharma. Co., Ltd. (2013). Peptide compound cyclization method. *Patent WO2013100132A1*.
- [6] Zaretsky, S., Scully, C. C., Lough, A. J., and Yudin, A. K. (2013). Exocyclic control of turn induction in macrocyclic peptide scaffolds. *Chem. Eur. J.*, **19**(52), 17668–17672.
- [7] Nielsen, D. S., Hoang, H. N., Lohman, R. J., Hill, T. A., Lucke, A. J., Craik, D. J., Edmonds, D. J., Griffith, D. A., Rotter, C. J., Ruggeri, R. B., Price, D. A., Liras, S., and Fairlie, D. P. (2014). Improving on Nature: Making a Cyclic Heptapeptide Orally Bioavailable. Angew. *Chem. Int. Ed.*, **53**(45), 12059–12063.
- [8] Ahlbach, C. L., Lexa, K. W., Bockus, A. T., Chen, V., Crews, P., Jacobson, M. P., and Lokey, R. S. (2015). Beyond cyclosporine A: conformation-dependent passive membrane permeabilities of cyclic peptide natural products. *Future Med. Chem.*, 7(16), 2121–2130.
- [9] Bockus, A. T., Lexa, K. W., Pye, C. R., Kalgutkar, A. S., Gardner, J. W., Hund, K. C., Hewitt, W. M., Schwochert, J. A., Glassey, E., Price, D. A., Mathiowetz, A. M., Liras, S., Jacobson, M. P., and Lokey, R. S. (2015a). Probing the Physicochemical Boundaries of Cell Permeability and Oral Bioavailability in Lipophilic Macrocycles Inspired by Natural Products. J. Med. Chem., 58(11), 4581–4589.
- [10] Bockus, A. T., Schwochert, J. A., Pye, C. R., Townsend, C. E., Sok, V., Bednarek, M. A.,

- and Lokey, R. S. (2015b). Going Out on a Limb: Delineating the Effects of β-Branching, N-Methylation, and Side Chain Size on the Passive Permeability, Solubility, and Flexibility of Sanguinamide A Analogues. *J. Med. Chem.*, **58**(18), 7409–7418.
- [11] Hewitt, W. M., Leung, S. S., Pye, C. R., Ponkey, A. R., Bednarek, M., Jacobson, M. P., and Lokey, R. S. (2015). Cell-permeable cyclic peptides from synthetic libraries inspired by natural products. *J. Am. Chem. Soc.*, **137**(2), 715–721.
- [12] Lewis, I., Schaefer, M., Wagner, T., Oberer, L., Sager, E., Wipfli, P., and Vorherr, T. (2015). A detailed investigation on conformation, permeability and PK properties of two related cyclohexapeptides. *Int. J. Pept. Res. Ther.*, 21(2), 205–221.
- [13] Marelli, U. K., Bezençon, J., Puig, E., Ernst, B., and Kessler, H. (2015). Enantiomeric cyclic peptides with different caco-2 permeability suggest carrier-mediated transport. *Chem. Eur. J.*, **21**(22), 8023–8027.
- [14] Nielsen, D. S., Lohman, R. J., Hoang, H. N., Hill, T. A., Jones, A., Lucke, A. J., and Fairlie, D. P. (2015). Flexibility versus Rigidity for Orally Bioavailable Cyclic Hexapeptides. *ChemBioChem*, **16**(16), 2289–2293.
- [15] Schwochert, J., Turner, R., Thang, M., Berkeley, R. F., Ponkey, A. R., Rodriguez, K. M., Leung, S. S., Khunte, B., Goetz, G., Limberakis, C., Kalgutkar, A. S., Eng, H., Shapiro, M. J., Mathiowetz, A. M., Price, D. A., Liras, S., Jacobson, M. P., and Lokey, R. S. (2015). Peptide to Peptoid Substitutions Increase Cell Permeability in Cyclic Hexapeptides. *Org. Lett.*, 17(12), 2928–2931.
- [16] Wang, C. K., Northfield, S. E., Swedberg, J. E., Colless, B., Chaousis, S., Price, D. A., Liras, S., and Craik, D. J. (2015). Exploring experimental and computational markers of cyclic peptides: Charting islands of permeability. *Eur. J. Med. Chem.*, 97, 202–213.
- [17] Fouché, M., Schäfer, M., Berghausen, J., Desrayaud, S., Blatter, M., Piéchon, P., Dix, I., Martingarcia, A., and Roth, H. J. (2016). Design and Development of a Cyclic Decapeptide Scaffold with Suitable Properties for Bioavailability and Oral Exposure. *ChemMedChem*, 11(10), 1048–1059.
- [18] Frost, J. R., Scully, C. C., and Yudin, A. K. (2016). Oxadiazole grafts in peptide macrocycles. *Nat. Chem.*, **8**(12), 1105–1111.
- [19] Furukawa, A., Townsend, C. E., Schwochert, J., Pye, C. R., Bednarek, M. A., and Lokey, R. S. (2016). Passive Membrane Permeability in Cyclic Peptomer Scaffolds Is Robust to Extensive Variation in Side Chain Functionality and Backbone Geometry. *J. Med. Chem.*, 59(20), 9503–9512.
- [20] Hickey, J. L., Zaretsky, S., St Denis, M. A., Kumar Chakka, S., Morshed, M. M., Scully, C. C., Roughton, A. L., and Yudin, A. K. (2016). Passive Membrane Permeability of Macrocycles Can Be Controlled by Exocyclic Amide Bonds. *J. Med. Chem.*, 59(11), 5368–

- [21] Schwochert, J., Lao, Y., Pye, C. R., Naylor, M. R., Desai, P. V., Gonzalez Valcarcel, I. C., Barrett, J. A., Sawada, G., Blanco, M. J., and Lokey, R. S. (2016). Stereochemistry Balances Cell Permeability and Solubility in the Naturally Derived Phepropeptin Cyclic Peptides. ACS Med. Chem. Lett., 7(8), 757–761.
- [22] Boehm, M., Beaumont, K., Jones, R., Kalgutkar, A. S., Zhang, L., Atkinson, K., Bai, G., Brown, J. A., Eng, H., Goetz, G. H., Holder, B. R., Khunte, B., Lazzaro, S., Limberakis, C., Ryu, S., Shapiro, M. J., Tylaska, L., Yan, J., Turner, R., Leung, S. S., Ramaseshan, M., Price, D. A., Liras, S., Jacobson, M. P., Earp, D. J., Lokey, R. S., Mathiowetz, A. M., and Menhaji-Klotz, E. (2017). Discovery of Potent and Orally Bioavailable Macrocyclic Peptide-Peptoid Hybrid CXCR7 Modulators. *J. Med. Chem.*, 60(23), 9653–9663.
- [23] Price, D. A., Eng, H., Farley, K. A., Goetz, G. H., Huang, Y., Jiao, Z., Kalgutkar, A. S., Kablaoui, N. M., Khunte, B., Liras, S., Limberakis, C., Mathiowetz, A. M., Ruggeri, R. B., Quan, J. M., and Yang, Z. (2017). Comparative pharmacokinetic profile of cyclosporine (CsA) with a decapeptide and a linear analogue. *Org. Biomol. Chem.*, 15(12), 2501–2506.
- [24] Pye, C. R., Hewitt, W. M., Schwochert, J., Haddad, T. D., Townsend, C. E., Etienne, L., Lao, Y., Limberakis, C., Furukawa, A., Mathiowetz, A. M., Price, D. A., Liras, S., and Lokey, R. S. (2017). Nonclassical Size Dependence of Permeation Defines Bounds for Passive Adsorption of Large Drug Molecules. *J. Med. Chem.*, 60(5), 1665–1672.
- [25] Buckton, L. K. and McAlpine, S. R. (2018). Improving the Cell Permeability of Polar Cyclic Peptides by Replacing Residues with Alkylated Amino Acids, Asparagines, and d-Amino Acids. Org. Lett., 20(3), 506–509.
- [26] Chugai Pharma. Co., Ltd. (2018). Cyclic peptide compound having high membrane permeability, and library containing same. *Patent WO2018225864A1*.
- [27] García-Pindado, J., Willemse, T., Goss, R., Maes, B. U., Giralt, E., Ballet, S., and Teixidó, M. (2018). Bromotryptophans and their incorporation in cyclic and bicyclic privileged peptides. *Biopolymers*, 109(10), e23112.
- [28] Kaneda, M., Kawaguchi, S., Fujii, N., Ohno, H., and Oishi, S. (2018). Structure-Activity Relationship Study on Odoamide: Insights into the Bioactivities of Aurilide-Family Hybrid Peptide-Polyketides. *ACS Med. Chem. Lett.*, **9**(4), 365–369.
- [29] Lee, L. L., Buckton, L. K., and McAlpine, S. R. (2018). Converting polar cyclic peptides into membrane permeable molecules using N-methylation. *Pept. Sci.*, **110**(3), e24063.
- [30] Naylor, M. R., Ly, A. M., Handford, M. J., Ramos, D. P., Pye, C. R., Furukawa, A., Klein, V. G., Noland, R. P., Edmondson, Q., Turmon, A. C., Hewitt, W. M., Schwochert, J., Townsend, C. E., Kelly, C. N., Blanco, M. J., and Lokey, R. S. (2018). Lipophilic Permeability Efficiency Reconciles the Opposing Roles of Lipophilicity in Membrane

- Permeability and Aqueous Solubility. J. Med. Chem., 61(24), 11169–11182.
- [31] Ramalho, S. D., Wang, C. K., King, G. J., Byriel, K. A., Huang, Y. H., Bolzani, V. S., and Craik, D. J. (2018). Synthesis, Racemic X-ray Crystallographic, and Permeability Studies of Bioactive Orbitides from Jatropha Species. *J. Nat. Prod.*, 81(11), 2436–2445.
- [32] Ono, S., Naylor, M. R., Townsend, C. E., Okumura, C., Okada, O., and Lokey, R. S. (2019). Conformation and Permeability: Cyclic Hexapeptide Diastereomers. *J. Chem. Inf. Model.*, 59(6), 2952–2963.
- [33] Barlow, N., Chalmers, D. K., Williams-Noonan, B. J., Thompson, P. E., Norton, R. S., and Thompson, P. E. (2020). Improving Membrane Permeation in the beyond Rule-of-Five Space by Using Prodrugs to Mask Hydrogen Bond Donors. *ACS Chem. Biol.*, **15**(8), 2070–2078.
- [34] Furukawa, A., Schwochert, J., Pye, C. R., Asano, D., Edmondson, Q. D., Turmon, A. C., Klein, V. G., Ono, S., Okada, O., and Lokey, R. S. (2020). Drug-Like Properties in Macrocycles above MW 1000: Backbone Rigidity versus Side-Chain Lipophilicity. *Angew. Chem. Int. Ed.*, 132(48), 21755–21761.
- [35] Hosono, Y., Morimoto, J., Townsend, C. E., Kelly, C. N., Naylor, M. R., Lee, H. W., Scott Lokey, R., and Sando, S. (2020). Amide-to-Ester Substitution Improves Membrane Permeability of a Cyclic Peptide without Altering Its Three-Dimensional Structure. *ChemRxiv*. DOI: 10.26434/chemrxiv.12272861.v1.
- [36] Le Roux, A., Blaise, É., Boudreault, P. L., Comeau, C., Doucet, A., Giarrusso, M., Collin, M. P., Neubauer, T., Kölling, F., Göller, A. H., Seep, L., Tshitenge, D. T., Wittwer, M., Kullmann, M., Hillisch, A., Mittendorf, J., and Marsault, E. (2020). Structure-Permeability Relationship of Semipeptidic Macrocycles-Understanding and Optimizing Passive Permeability and Efflux Ratio. *J. Med. Chem.*, 63(13), 6774–6783.
- [37] Townsend, C. E., Naylor, M. R., Jason, E., Pye, C. R., Schwochert, J. A., Edmondson, Q., and Lokey, R. S. (2020). The passive permeability landscape around geometrically diverse hexa- And heptapeptide macrocycles. *ChemRxiv*, pages 1–21. DOI: 10.26434/chemrxiv.13335941.v1.
- [38] Comeau, C., Ries, B., Stadelmann, T., Tremblay, J., Poulet, S., Fröhlich, U., Côté, J., Boudreault, P. L., Derbali, R. M., Sarret, P., Grandbois, M., Leclair, G., Riniker, S., and Marsault, É. (2021). Modulation of the Passive Permeability of Semipeptidic Macrocycles: N- And C-Methylations Fine-Tune Conformation and Properties. *J. Med. Chem.*, 64(9), 5365–5383.
- [39] Golosov, A. A., Flyer, A. N., Amin, J., Babu, C., Gampe, C., Li, J., Liu, E., Nakajima, K., Nettleton, D., Patel, T. J., Reid, P. C., Yang, L., and Monovich, L. G. (2021). Design of Thioether Cyclic Peptide Scaffolds with Passive Permeability and Oral Exposure. *J. Med.*

- Chem., 64(5), 2622–2633.
- [40] Kelly, C. N., Townsend, C. E., Jain, A. N., Naylor, M. R., Pye, C. R., Schwochert, J., and Lokey, R. S. (2021). Geometrically Diverse Lariat Peptide Scaffolds Reveal an Untapped Chemical Space of High Membrane Permeability. *J. Am. Chem. Soc.*, **143**(2), 705–714.
- [41] Lee, D., Lee, S., Choi, J., Song, Y. K., Kim, M. J., Shin, D. S., Bae, M. A., Kim, Y. C., Park, C. J., Lee, K. R., Choi, J. H., and Seo, J. (2021). Interplay among Conformation, Intramolecular Hydrogen Bonds, and Chameleonicity in the Membrane Permeability and Cyclophilin A Binding of Macrocyclic Peptide Cyclosporin O Derivatives. *J. Med. Chem.*, 64(12), 8272-8286.
- [42] Wang, S., König, G., Roth, H.-J., Fouché, M., Rodde, S., and Riniker, S. (2021). Effect of Flexibility, Lipophilicity, and the Location of Polar Residues on the Passive Membrane Permeability of a Series of Cyclic Decapeptides. *J. Med. Chem.*, **64**(17), 12761–12773.
- [43] Bhardwaj, G., O'Connor, J., Rettie, S., Huang, Y.-H., Ramelot, T. A., Mulligan, V. K., Alpkilic, G. G., Palmer, J., Bera, A. K., Bick, M. J., Di Piazza, M., Li, X., Hosseinzadeh, P., Craven, T. W., Tejero, R., Lauko, A., Choi, R., Glynn, C., Dong, L., Griffin, R., van Voorhis, W. C., Rodriguez, J., Stewart, L., Montelione, G. T., Craik, D., and Baker, D. (2022). Accurate de novo design of membrane-traversing macrocycles. *Cell*, **185**(19), 3520–3532.
- [44] Lee, D., Kang, J. A., Lim, C., Bae, S., Choi, J., Park, M., Kim, Y. C., Cho, Y., Park, S. G., and Seo, J. (2022). Entry inhibition of hepatitis B virus using cyclosporin O derivatives with peptoid side chain incorporation. *Bioorg. Med. Chem.*, 116862.
- [45] Saunders, G. J. and Yudin, A. K. (2022). Property-driven development of passively permeable macrocyclic scaffolds using heterocycles. *Angew. Chem. Int. Ed.*, **134**(33), e202206866.
- [46] Taechalertpaisarn, J., Ono, S., Okada, O., Johnstone, T. C., and Lokey, R. S. (2022). A New Amino Acid for Improving Permeability and Solubility in Macrocyclic Peptides through Side Chain-to-Backbone Hydrogen Bonding. *J. Med. Chem.*, 65(6), 5072–5084.
- [47] Tamura, T., Inoue, M., Yoshimitsu, Y., Hashimoto, I., Ohashi, N., Tsumura, K., Suzuki, K., Watanabe, T., and Hohsaka, T. (2022). Chemical synthesis and cell-free expression of thiazoline ring-bridged cyclic peptides and their properties on biomembrane permeability. *Bull. Chem. Soc. Jpn.*, **95**(2), 359–366.