

Marquette University

e-Publications@Marquette

Chemistry Faculty Research and Publications

Chemistry, Department of

2019

Design and Evaluation of Heterobivalent PAR1–PAR2 Ligands as Antagonists of Calcium Mobilization

Mark W. Majewski
Marquette University

Disha M. Gandhi
Marquette University

Ricardo Rosas Jr.
Marquette University

Revathi Kodall
University of Wisconsin - Milwaukee

Leggy A. Arnold
University of Wisconsin - Milwaukee

See next page for additional authors

Follow this and additional works at: https://epublications.marquette.edu/chem_fac

 Part of the [Chemistry Commons](#)

Recommended Citation

Majewski, Mark W.; Gandhi, Disha M.; Rosas, Ricardo Jr.; Kodall, Revathi; Arnold, Leggy A.; and Dockendorff, Chris, "Design and Evaluation of Heterobivalent PAR1–PAR2 Ligands as Antagonists of Calcium Mobilization" (2019). *Chemistry Faculty Research and Publications*. 966.
https://epublications.marquette.edu/chem_fac/966

Authors

Mark W. Majewski, Disha M. Gandhi, Ricardo Rosas Jr., Revathi Kodall, Leggy A. Arnold, and Chris Dockendorff

Marquette University

e-Publications@Marquette

Chemistry Faculty Research and Publications/College of Arts and Science

This paper is NOT THE PUBLISHED VERSION; but the author's final, peer-reviewed manuscript.

The published version may be accessed by following the link in the citation below.

ACS Medicinal Chemistry Letters, Vol. 10, No. 1 (2019): 121-126. [DOI](#). This article is © American Chemical Society and permission has been granted for this version to appear in [e-Publications@Marquette](#). American Chemical Society does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from American Chemical Society.

Design and Evaluation of Heterobivalent PAR1–PAR2 Ligands as Antagonists of Calcium Mobilization

Mark W. Majewski

Department of Chemistry, Marquette University, Milwaukee, WI

Disha M. Gandhi

Department of Chemistry, Marquette University, Milwaukee, WI

Ricardo Roasas, Jr.

Department of Chemistry, Marquette University, Milwaukee, WI

Revathi Kodali

Department of Chemistry and Biochemistry, Milwaukee Institute for Drug Discovery, University of Wisconsin-Milwaukee, WI

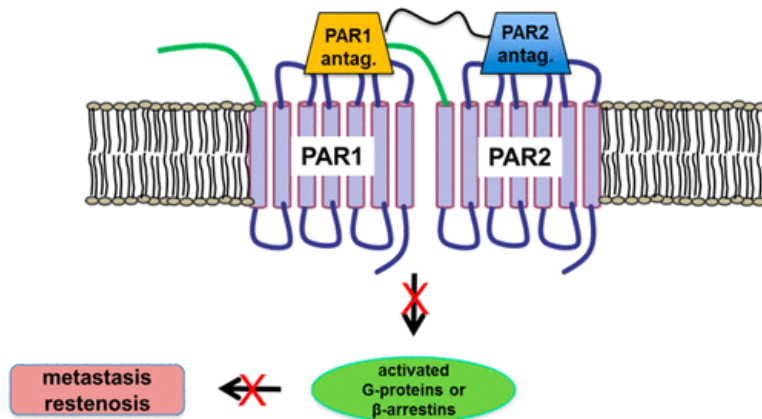
Leggy. A. Arnold

Department of Chemistry and Biochemistry, Milwaukee Institute for Drug Discovery, University of Wisconsin-Milwaukee, WI

Chris Dockendorff

Department of Chemistry, Marquette University, Milwaukee, WI

Abstract



A novel class of bivalent ligands targeting putative protease-activated receptor (PAR) heteromers has been prepared based upon reported antagonists for the subtypes PAR1 and PAR2. Modified versions of the PAR1 antagonist RWJ-58259 containing alkyne adapters were connected via cycloaddition reactions to azide-capped polyethylene glycol (PEG) spacers attached to imidazopyridazine-based PAR2 antagonists. Initial studies of the PAR1–PAR2 antagonists indicated that they inhibited G α q-mediated calcium mobilization in endothelial and cancer cells driven by both PAR1 and PAR2 agonists. Compounds of this novel class hold promise for the prevention of restenosis, cancer cell metastasis, and other proliferative disorders.

Keywords:

[Bivalent ligand](#); [calcium mobilization](#); [metastasis](#); [PAR1 antagonist](#); [PAR2 antagonist](#); [protease-activated receptor](#); [restenosis](#)

Protease-activated receptors (PARs) are a unique family of class A G-protein-coupled receptors (GPCRs) that are activated by extracellular proteases, which reveal a tethered ligand at the N-terminus.^(1,2) Self-activation of PARs by their tethered ligand agonists leads to a wide range of cellular responses, in part due to the fact that PARs are highly expressed in different tissues with varying signaling components; they can also be activated by different proteases that cleave at different locations on the N-terminus.⁽³⁾ The unusual complexity of PAR-mediated signaling is further increased by the potential for PARs and other GPCRs to form multireceptor complexes in cell membranes.⁽⁴⁾ More specifically, evidence has emerged in recent years that PARs form homomeric and heteromeric complexes among the four different PAR subtypes, and the signals mediated by these complexes are distinct from those of the monomers.^(5–7) Additionally, the N-terminus of one PAR subtype can directly activate a neighboring PAR.⁽⁸⁾

The range of productive and pathological signaling for which PARs have been implicated has prompted their study as potential targets for numerous indications, including thrombosis, inflammation, stroke, kidney disease, reperfusion injury, and cancer cell metastasis (vide infra). Despite their

therapeutic promise, to our knowledge only a few PAR modulators have thus far reached clinical stages, all as antithrombotic agents inhibiting platelet activation.⁽⁹⁻¹²⁾

The present lack of clinical PAR modulators for other indications may reflect in part the pleiotropic signaling of PARs, which may complicate the selective inhibition of pathological signals without adversely affecting normal signaling. For example, PAR1 antagonists may prevent thrombosis via inhibition of PAR1 on platelets, while concurrently interfering with endothelial barrier integrity by inhibiting normal PAR1 signaling in endothelium. This has inspired our recent efforts to identify biased ligands that may inhibit or activate only a subset of PAR1-mediated signaling pathways.⁽¹³⁻¹⁵⁾

An alternative therapeutic approach could utilize heterobivalent ligands to selectively target the differential signaling mediated by PAR heteromeric complexes (Figure 1). To our knowledge, no ligands selective for PAR heteromers have been reported. Evidence has been accumulating in recent years that GPCRs frequently form oligomers in vitro, but the in vivo relevance of these oligomers has been harder to quantify, in part due to a lack of adequate chemical tools.⁽⁴⁾ The concept of bivalent ligands for multimeric GPCRs was pioneered by Portoghese nearly 40 years ago,⁽¹⁶⁾ and this strategy has been used to generate compounds primarily for the study of CNS GPCRs.^(17,18) Recently, promising in vivo data have been obtained that suggest that bivalent ligands can modulate GPCRs in a manner distinct from that of their monovalent counterparts.⁽¹⁹⁻²²⁾ This approach holds particular promise for PARs, as the differential tissue expression of PAR subtypes could permit tissue-selective targeting of PAR heteromers using heterobivalent ligands. This is best exemplified by the fact that PAR2 is not expressed on human platelets; therefore, we reasoned that PAR2-directed heterobivalent ligands could permit the selective modulation of signaling by PAR2-containing heteromers in vascular tissues without adversely affecting platelet activation and hemostasis.

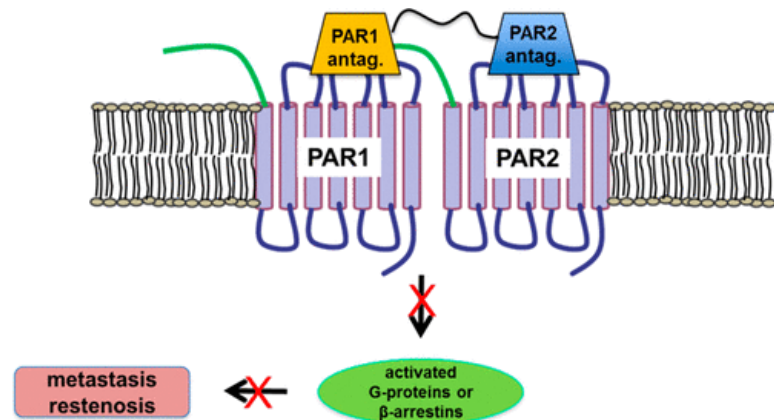
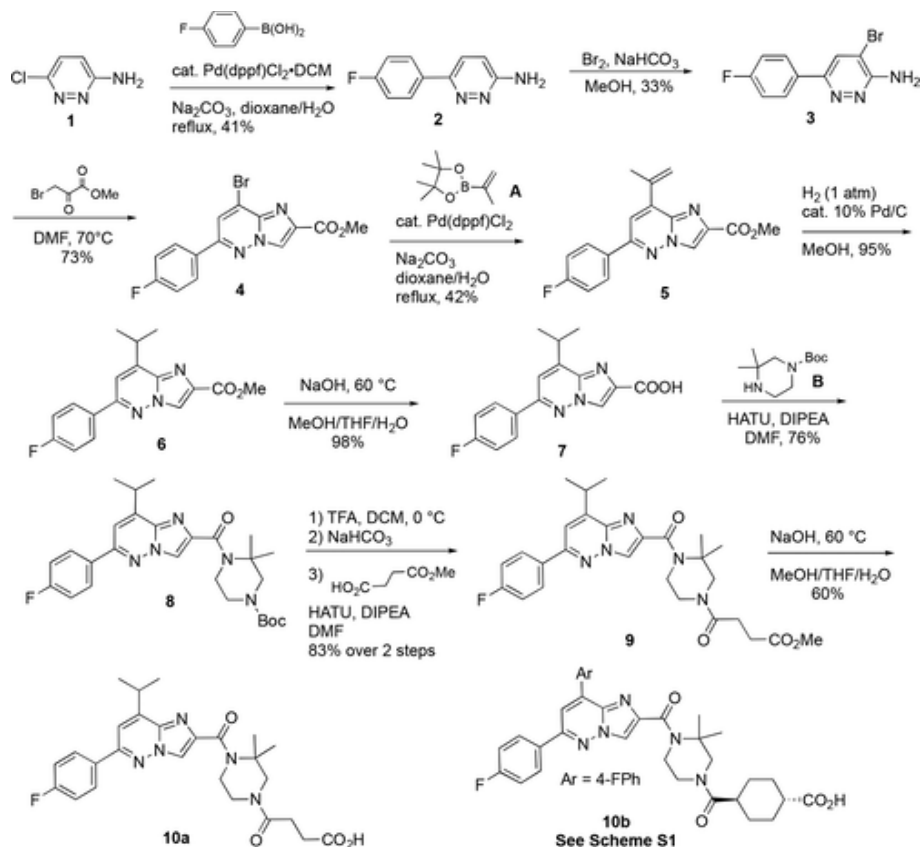


Figure 1. Proposed heterobivalent PAR ligands.

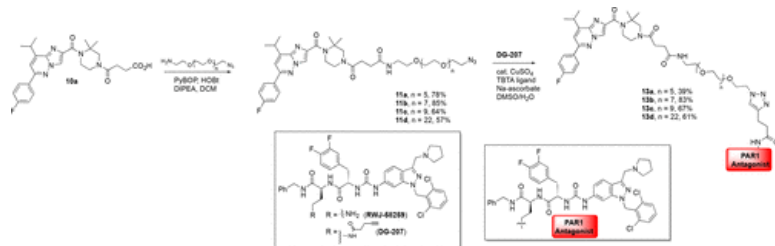
Mueller and colleagues presented evidence that thrombin-enhanced migration of melanoma cells is driven by PAR1 and PAR2, in a manner consistent with the “direct transactivation” of PAR2 by thrombin-activated PAR1.⁽²³⁾ Bar-Shavit has also reported synergistic effects of PAR1 and PAR2 activation in tumor development^(24,25) Kuliopulos reported that signaling by PAR1–PAR2 heteromers may be implicated in restenosis, the dangerous narrowing of blood vessels which occurs in a significant fraction of patients after percutaneous interventions (PCIs).⁽²⁶⁾

We hypothesize that heterobivalent antagonists may act selectively at putative PAR1–PAR2 heteromers and thus may act to inhibit cancer cell metastasis and proliferative processes such as restenosis, while minimizing impacts on normal PAR signaling. PAR1 antagonists have been investigated for restenosis in animal models,^(27,28) and individual PAR1^(29,30) and PAR2⁽³¹⁾ antagonists have been studied in cancer cell metastasis and invasion. To our knowledge, however, none of these studies has progressed to clinical stages for these indications. One complication may arise from the fact that the tethered ligand of PAR1 can directly transactivate a neighboring PAR2 receptor, which could possibly happen even in the presence of a PAR1 antagonist.⁽⁸⁾ Together, these observations make the preparation of multivalent PAR ligands an attractive strategy with benefits that may extend beyond the administration of multiple separate ligands. Herein we describe our initial efforts toward the synthesis and study of heterobivalent ligands targeting PAR1 and PAR2.

The primary considerations for the design of heterobivalent ligands are as follows: 1. What monovalent ligands should be used? 2. What spacers should be used to connect them? 3. Where should the spacer be attached to each ligand? Based on its published SAR data and potential for diverse modifications, we elected to utilize the PAR1 antagonist RWJ-58259 as the first PAR1 scaffold for our bivalent ligands^(27,32) and an imidazopyridazine scaffold reported by Vertex as the PAR2 antagonist.⁽³³⁾ To connect the ligands, we elected to first utilize commercially available polyethylene glycol (PEG)-based spacers with a variety of lengths, particularly for their beneficial physicochemical properties, especially increased water solubility. Also beneficial is the fact that bivalent ligands with PEG spacers with excess “slack” may pay less of an entropic penalty upon binding relative to those with more hydrophobic spacers,⁽³⁴⁾ presumably because hydrophilic PEGs can maintain flexibility in water and do not require highly ordered solvation shells. The use of commercially available amino-PEG-azide spacers permits convenient copper-catalyzed alkyne/azide cycloadditions (CuAAC), suitable for the connection of two appropriately functionalized ligands via the PEG spacer under diverse conditions.⁽³⁵⁾ We recently reported the synthesis of an alkyne-tethered version of RWJ-58259, which retained significant potency at PAR1.⁽¹⁵⁾ Based on the SARs published for the imidazopyridazine reported by Vertex, we elected to prepare carboxyl-substituted versions of these PAR2 antagonists using the reported synthetic route ([Scheme 1](#)).⁽³³⁾ 3-Amino-6-chloropyridazine (**1**) was subjected to Suzuki coupling with 4-fluorophenylboronic acid to yield the biarylamine **2**. Bromination followed by alkylation with bromomethylpyruvate yielded the imidazopyridazine **4**. Suzuki coupling with the propenylboronic ester A gave **5**, and hydrogenation provided the ester **6**. Hydrolysis followed by coupling with piperazine B yielded amide **8**. Removal of the Boc group, coupling with succinic acid monomethyl ester, and hydrolysis of the resulting ester gave carboxylic acid **10a**. PAR2 antagonists containing an arene substituent in place of the isopropyl group of **10a** and a cyclohexyl carboxylic acid in place of the eastern ethylene group were among numerous analogs previously reported;⁽³³⁾ therefore, carboxylic acid **10b** was additionally prepared ([Scheme S1](#)). Both of the carboxylic acids **10a** and **10b** were confirmed to be highly potent antagonists of PAR2 (vide infra), so we proceeded to couple them to a variety of PEG-based spacers ([Schemes 2](#) and [S2](#)). Amide coupling with amino(PEG)azides, followed by CuAAC⁽³⁶⁾ with the previously synthesized RWJ-58259-based alkyne **DG-207**,⁽¹⁵⁾ yielded heterobivalent ligands **13a–d**. Control compounds **15–18** composed of the monovalent ligands with attached PEG spacers are depicted in [Figure S1](#).



Scheme 1. Synthesis of PAR2 Antagonist with Carboxylic Acid Adapter Based on Reported Imidazopyridazines



Scheme 2. Assembly of Heterobivalent PAR1–PAR2 Antagonists

During the course of our studies, Marshall and colleagues reported several X-ray crystal structures of modified PAR2, including a cocrystal of PAR2 with the inhibitor AZ3451 at an allosteric site at the side of the receptor.^[37] The structural similarities between **10a** and AZ3451 led us to hypothesize that they may share a binding site on PAR2, which was supported by rigid protein docking studies (Figure 2a)^[38] and is consistent with the allosteric mode of inhibition recently reported by Fairlie for the Vertex^[33] imidazopyridazine I-191.^[39] Compound **10a** docks into the lipophilic pocket at the side of PAR2 in a similar pose to AZ3451, with both molecules possessing a heterocyclic nitrogen capable of accepting a hydrogen bond from Tyr210.

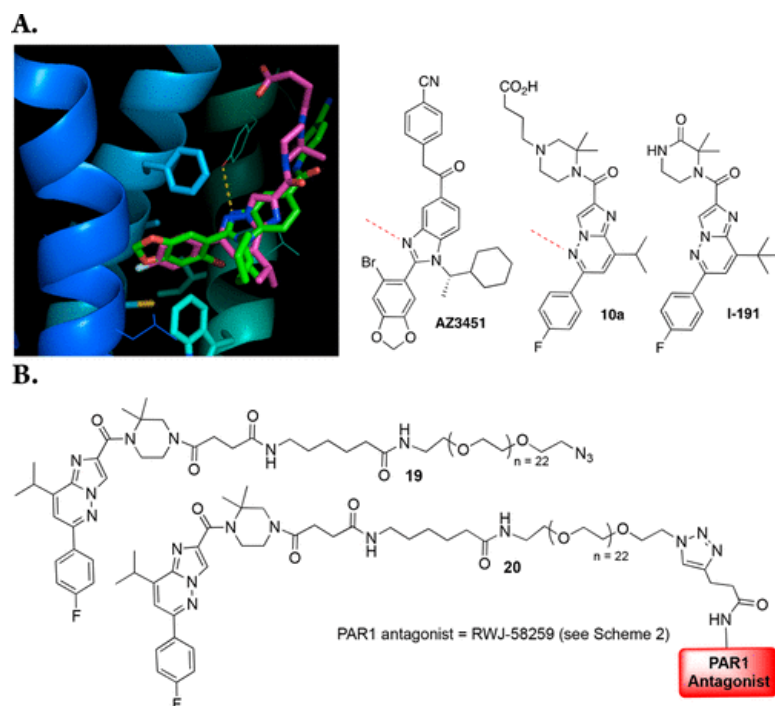


Figure 2. (A) X-ray structure of modified PAR2 with bound allosteric ligand AZ3451 (green) and docked ligand **10a** (pink). (B) Novel bivalent ligand **20** and control compound **19** possessing a PEG-aminoalkylamide spacer.

The position of this binding site within the cell membrane suggests that the hydrophilic PEG spacer may be counterproductive and could explain the greatly decreased potency at PAR2 of our PEG-linked PAR2 antagonists. We addressed this potential issue by synthesizing modified spacers containing a terminal aminoalkylamide that could possess a higher affinity for the cell membrane above the putative PAR2 binding site (Figure 2b and Scheme S3).

The ligands were tested in our intracellular calcium mobilization assay (iCa^{2+}) using the transformed human endothelial cell line EA.hy926, and this assay was also suitable for studying the signaling of the breast cancer cell line MDA-MB-231, which expresses both PAR1 and PAR2. Adherent cells were cultured in 96-well plates to confluence over ~ 48 h, then loaded with the fluorescent calcium binding dye Fluo-4/AM, according to our reported protocol.⁽⁴⁵⁾ Addition of the antagonists, followed by the relevant PAR peptide agonists TFLLRN-NH₂ (PAR1), SLIGKV-NH₂ (PAR2), or SFLLRN-NH₂ (PAR1/2), permitted the measurement of inhibition of Gq-driven signaling from both PAR1 and PAR2. All concentration–response curves show data from $N = 3$ on a single plate, fitted using four-variable nonlinear regression with GraphPad Prism v. 5. Error bars represent standard error of the mean (SEM) for the three measurements at each concentration.

The attachment of PEG spacers to the PAR1 antagonist RWJ-58259 and the PAR2 antagonist **10a** was tolerated, albeit with 5- to 70-fold decreases in potency. Half-maximal inhibitory concentration (IC₅₀) for the inhibition of TFLLRN-NH₂ (5 μ M) PAR1-mediated iCa^{2+} mobilization increased from 0.02 to 0.1 μ M for the PEG spacer-linked control **17** (Figure 3a). Compound **10a** inhibited SLIGKV-NH₂ (5 μ M) PAR2-mediated iCa^{2+} mobilization with an IC₅₀ of 0.1 μ M, and the PEG spacer-linked control **15** was significantly less potent (IC₅₀ = 7 μ M, Figure 3b). This is consistent with a report from Bunnett (published during revision of this manuscript) that describes an imidazopyridazine PAR2

antagonist that suffers an approximately 1000-fold drop in potency upon attachment of a PEG tether at a similar site.⁽⁴⁰⁾ These compounds also showed good potencies in analogous assays with MDA-MB-231 cancer cells (Figures 3c,d).

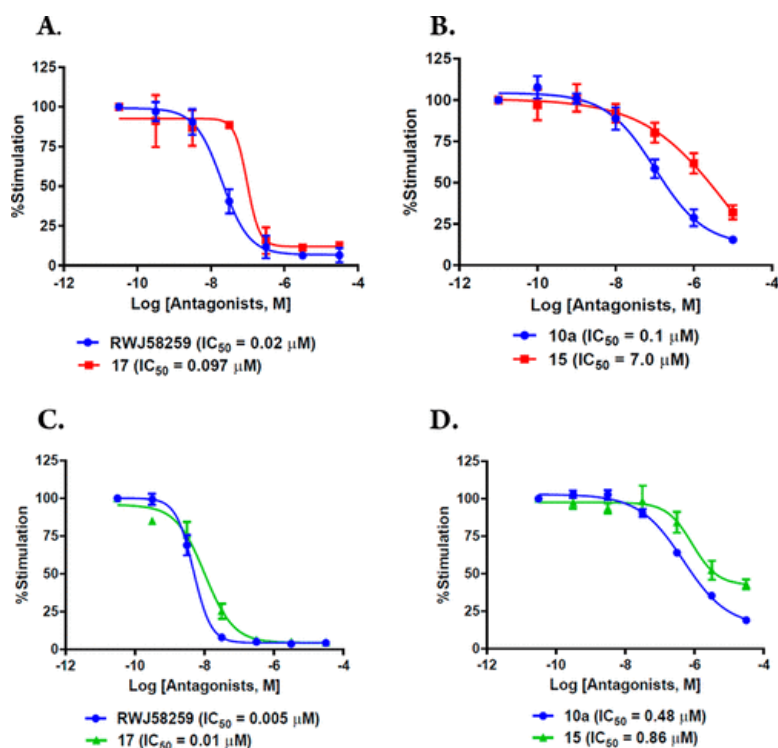


Figure 3. Inhibition of TFLLRN-NH₂ (5 μM) PAR1-mediated *i*Ca²⁺ mobilization by monovalent PAR1 ligand RWJ-58259 and spacer-linked control **17** (A) in EA.hy926 endothelial cells and (C) in MDA-MB-231 cancer cells; inhibition of SLIGKV-NH₂ (5 μM) PAR2-mediated *i*Ca²⁺ mobilization by monovalent PAR2 ligand **10a** and spacer-linked control **15** (B) in EA.hy926 endothelial cells and (D) in MDA-MB-231 cancer cells.

As described above, we proceeded to prepare bivalent ligands possessing spacers of different lengths, from shortest (21 atoms, **13a**) to longest (72 atoms, **13d**). To support their potential utility for future in vivo experiments, the stability of **13d** was measured in mouse plasma, and a half-life of 5.6 h was determined (see [Supporting Info](#) for details). All four ligands showed good inhibition of PAR1-driven (TFLLRN-NH₂) calcium mobilization in EA.hy926 cells, with comparable IC₅₀s ranging from 0.03 to 0.18 μM (Figure 4a). The efficacy of the longest ligand (**13d**) was higher than the others at the highest concentrations. All four ligands had much lower potency and efficacy as PAR2 antagonists, using SLIGKV-NH₂ as agonist (Figure 4b). An IC₅₀ could only be estimated from the concentration–response curve fitted to the data from **13d**, with an IC₅₀ of 3.3 μM, and with only partial inhibition at the highest concentration (31.6 μM). The decreased potencies and efficacies of the bivalent ligands at PAR2, particularly comparing these ligands to the PEG-linked PAR2 antagonist controls, may reflect a higher affinity of the bivalent ligands for PAR1, and/or a higher receptor density for PAR1, such that ligands may be binding significantly to monomeric PAR1.

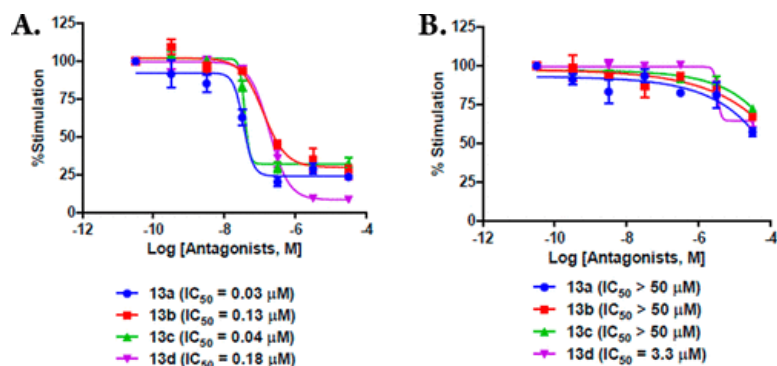


Figure 4. Inhibition of TFLLRN-NH₂ (5 μM) PAR1-mediated *i*Ca²⁺ mobilization (A) and SLIGKV-NH₂ (5 μM) PAR2-mediated *i*Ca²⁺ mobilization (B) by bivalent ligands **13a–d** in EA.hy926 endothelial cells.

Next, the bivalent ligands **13a–d** were tested for their ability to inhibit the PAR1/2 agonist SFLLRN-NH₂, dosed at 3.16 μM (Figure 5a). Again, the ligand with the longest spacer (**13d**) proved to be most potent, with an IC₅₀ of 0.15 μM. It was also compared to the control compounds composed of monovalent PAR1 (**17**) and PAR2 (**15**) ligands with spacers and their combination (Figure 5b). The combination of equal concentrations of **17** and **15** gave an IC₅₀ of 0.32 μM, resulting in an inhibition profile very similar to that of the bivalent ligand **13d**. The inability of the PAR2 ligand **15** to inhibit SFLLRN-NH₂ to any measurable degree suggests that its signaling is largely driven by PAR1 with EA.hy926 cells. Inhibition with the bivalent ligands derived from the PAR2 ligand **10b** was inferior to those derived from **10a**. These data are included in the [Supporting Information](#) (Figures S2–S4).

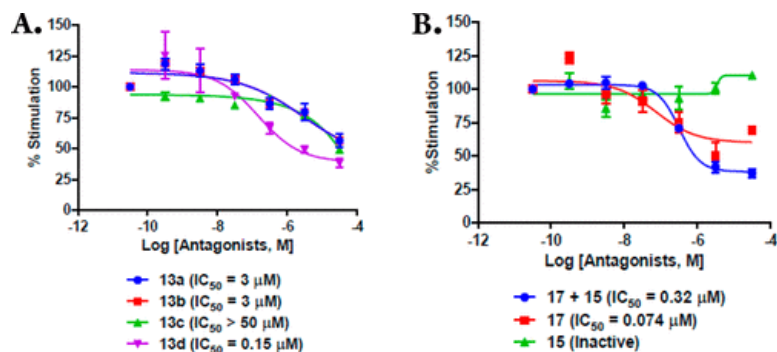


Figure 5. Inhibition of SFLLRN-NH₂ (3.16 μM) PAR1/2-mediated *i*Ca²⁺ mobilization by bivalent ligands **13a–d** (A) and individual and codosed monovalent control compounds (**17 + 15**) in EA.hy926 endothelial cells (B).

The bivalent ligand **13d** was next studied in the breast cancer cell line with all three agonists (Figure 6). It was most effective at the inhibition of TFLLRN-NH₂-driven calcium mobilization, with an IC₅₀ of 0.14 μM and excellent efficacy. The IC₅₀ for inhibition of SFLLRN-NH₂ was 3.3 μM, with lower efficacy. The inhibition of SLIGKV-NH₂ by **13d** was less efficient, with an IC₅₀ estimated at 3.5 μM, but with no inhibition observed at submicromolar concentrations. The bivalent ligand possessing a more hydrophobic spacer (**20**, Figure 2b) was also tested for its possible improved activity at PAR2; unfortunately, attachment of this spacer did not improve the inhibition of PAR2-mediated signaling (Figures S6–S8).

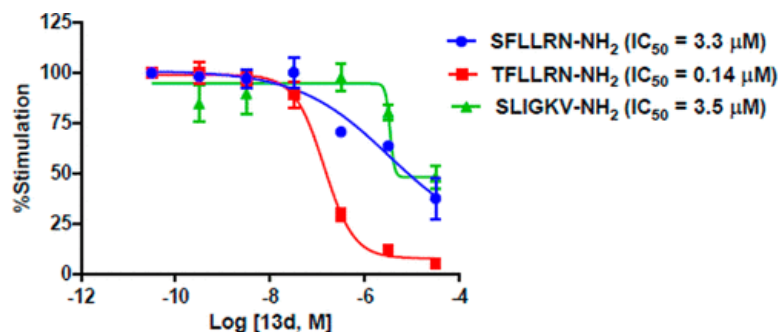


Figure 6. Inhibition of TFLLRN-NH₂ (5 μM) PAR1-mediated, SLIGKV-NH₂ (5 μM) PAR2-mediated, and SFLLRN-NH₂ (3.16 μM) PAR1/2-mediated *i*Ca²⁺ mobilization of **13d** in MDA-MB-231 breast cancer cells.

Finally, **13d** was tested for its ability to inhibit the natural PAR1- and PAR2-activating proteases thrombin (Figure S9) and trypsin (Figure S10). Compound **13d** inhibited 1 nM thrombin with an IC₅₀ of 0.36 μM in Ea.hy926 cells, but interestingly, the spacer-linked control **17** was ~10× more potent. The PAR2 antagonist **10a** was a potent inhibitor of 5 nM trypsin (IC₅₀ = 0.002 μM), but attachment of a spacer (**15**) abrogated its activity, and the bivalent ligand **13d** also showed no inhibition of trypsin.

We have reported the first examples of bivalent PAR1–PAR2 antagonists, and we demonstrated that the optimal compound **13d** can perform similarly to the combination of monovalent control ligands in the inhibition of intracellular calcium mobilization in the transformed endothelial cell line EA.hy926, as well as the epithelial breast cancer cell line MDA-MB-231. However, the decrease in potency observed upon attachment of PEG-based spacers to the monovalent PAR1 and PAR2 ligands means that the ligands are less potent than the combination of monovalent ligands without spacers attached, though there is always a significant disadvantage of dosing multiple drugs to obtain a desired therapeutic effect. These considerations may be less important than the ability of a heterobivalent ligand to selectively inhibit a putative heteromeric receptor complex that drives a pathological effect, such as metastasis, without interfering with healthy cell signaling. We have not yet obtained evidence that the bivalent ligands disclosed here selectively inhibit putative PAR1–PAR2 complexes; an example of such evidence would be biphasic concentration–response curves, where the ligands inhibit a population of heteromers at lower concentrations. However, the ability to detect low concentrations of such complexes is limited by the precision of the calcium mobilization assay. Receptor binding assays with labeled ligands are planned that would be more suitable for the detection of low populations of heteromers, and studies on PAR-driven cancer cell migration are also underway. The main weakness of the present ligands is their decrease in potency at PAR2 upon attachment of spacers to the PAR2 antagonist scaffolds, and therefore, we are presently investigating alternative PAR2 antagonists and spacers. Bivalent PAR1–PAR2 antagonists are a novel class of ligands that may hold promise for the inhibition of cancer cell metastasis, restenosis, and other proliferative diseases.

Supporting Information

The Supporting Information is available free of charge on the [ACS Publications website](https://doi.org/10.1021/acsmchemlett.8b00538) at DOI: [10.1021/acsmchemlett.8b00538](https://doi.org/10.1021/acsmchemlett.8b00538).

- Additional abbreviations; Schemes S1–S3; Figures S1–S10; assay protocols; plasma stability assay protocol and data for **13d**; synthetic protocols; and characterization data (¹H NMR, ¹³C NMR, and LC–MS chromatograms) ([PDF](#))

- PDF
 - [ml8b00538_si_001.pdf \(5.59 MB\)](#)

Acknowledgments

We thank Dr. Hartmut Weiler, Irene Hernandez, and Trudy Holyst (Blood Research Institute) for assistance with cell culture and assay troubleshooting, Dr. Michael Dwinell and Donna McAllister (Medical College of Wisconsin) for helpful advice and a sample of MDA-MB-231 cells, Prof. Nicolas Moitessier for providing access to FITTED docking software, Dr. Rachel Jones (Medical College of Wisconsin) for advice regarding the CuAAC reaction, Elliot DeMilo (Univ. Wisconsin-Milwaukee) for assistance with the stability study, and Dr. Sheng Cai (Marquette University) for assistance with LC-MS and NMR instruments. We thank ACD/Labs (NMR processing) and ChemAxon (NMR prediction and property prediction) for providing access to software.

ABBREVIATIONS	
Boc	<i>tert</i> -butoxycarbonyl
CuAAC	copper-catalyzed alkyne/azide cycloadditions
DCE	1,2-dichloroethane
DCM	dichloromethane
DIEA	<i>N,N</i> -diisopropylethylamine
DMAP	4-dimethylaminopyridine
DPPF	1,1'-bis(diphenylphosphino)ferrocene
EDC	1-ethyl-3-(3-(dimethylamino)propyl)carbodiimide
GPCR	G-protein coupled receptor
HATU	hexafluorophosphate azabenzotriazole tetramethyl uronium
HOBt	1-hydroxybenzotriazole
IC ₅₀	half-maximal inhibitory concentration
<i>i</i> Ca ²⁺	intracellular calcium mobilization
MI	myocardial infarction
PAR	protease-activated receptor
PCI	percutaneous interventions
PyBOP	(benzotriazol-1-yloxy)tripyrrolidinophosphonium hexafluorophosphate
SEM	standard error of the mean
TBTA	tris(benzyltriazolylmethyl)amine

References

1. Vu, T.-K. H.; Hung, D. T.; Wheaton, V. I.; Coughlin, S. R. Molecular Cloning of a Functional Thrombin Receptor Reveals a Novel Proteolytic Mechanism of Receptor Activation. *Cell* 1991, 64, 1057–1068, DOI: 10.1016/0092-8674(91)90261-V
2. Hamilton, J. R.; Trejo, J. Challenges and Opportunities in Protease-Activated Receptor Drug Development. *Annu. Rev. Pharmacol. Toxicol.* 2017, 57, 349–373, DOI: 10.1146/annurev-pharmtox-011613-140016
3. Bouwens, E.; Stavenuiter, F.; Mosnier, L. O. Mechanisms of Anticoagulant and Cytoprotective Actions of the Protein C Pathway. *J. Thromb. Haemostasis* 2013, 11, 242–253, DOI: 10.1111/jth.12247

4. Gomes, I.; Ayoub, M. A.; Fujita, W.; Jaeger, W. C.; Pflieger, K. D. G.; Devi, L. A. G. Protein–Coupled Receptor Heteromers. *Annu. Rev. Pharmacol. Toxicol.* 2016, 56, 403– 425, DOI: 10.1146/annurev-pharmtox-011613-135952
5. Lin, H.; Trejo, J. Transactivation of the PAR1-PAR2 Heterodimer by Thrombin Elicits β -Arrestin-Mediated Endosomal Signaling. *J. Biol. Chem.* 2013, 288, 11203– 11215, DOI: 10.1074/jbc.M112.439950
6. Lin, H.; Liu, A. P.; Smith, T. H.; Trejo, J. Cofactoring and Dimerization of Proteinase-Activated Receptors. *Pharmacol. Rev.* 2013, 65, 1198– 1213, DOI: 10.1124/pr.111.004747
7. Gieseler, F.; Ungefroren, H.; Settmacher, U.; Hollenberg, M. D.; Kaufmann, R. Proteinase-Activated Receptors (PARs) - Focus on Receptor-Receptor-Interactions and Their Physiological and Pathophysiological Impact. *Cell Commun. Signaling* 2013, 11, 86, DOI: 10.1186/1478-811X-11-86
8. O'Brien, P. J.; Prevost, N.; Molino, M.; Hollinger, M. K.; Woolkalis, M. J.; Woulfe, D. S.; Brass, L. F. Thrombin Responses in Human Endothelial Cells. Contributions From Receptors Other Than PAR1 Include the Transactivation of PAR2 by Thrombin-Cleaved PAR1. *J. Biol. Chem.* 2000, 275, 13502– 13509, DOI: 10.1074/jbc.275.18.13502
9. Chackalamannil, S.; Wang, Y.; Greenlee, W. J.; Hu, Z.; Xia, Y.; Ahn, H.-S.; Boykow, G.; Hsieh, Y.; Palamanda, J.; Agans-Fantuzzi, J.; Kurowski, S.; Graziano, M.; Chintala, M. Discovery of a Novel, Orally Active Himbacine-Based Thrombin Receptor Antagonist (SCH 530348) with Potent Antiplatelet Activity. *J. Med. Chem.* 2008, 51, 3061– 3064, DOI: 10.1021/jm800180e
10. Wiviott, S. D.; Flather, M. D.; O'Donoghue, M. L.; Goto, S.; Fitzgerald, D. J.; Cura, F.; Aylward, P.; Guetta, V.; Dudek, D.; Contant, C. F.; Angiolillo, D. J.; Bhatt, D. L. *LANCELOT-CAD Investigators. Randomized Trial of Atopaxar in the Treatment of Patients with Coronary Artery Disease: the Lessons From Antagonizing the Cellular Effect of Thrombin–Coronary Artery Disease Trial.* *Circulation* 2011, 123, 1854– 1863, DOI: 10.1161/CIRCULATIONAHA.110.001404
11. Gurbel, P. A.; Bliden, K. P.; Turner, S. E.; Tantry, U. S.; Gesheff, M. G.; Barr, T. P.; Covic, L.; Kuliopulos, A. Cell-Penetrating Pepducin Therapy Targeting PAR1 in Subjects with Coronary Artery Disease. *Arterioscler., Thromb., Vasc. Biol.* 2016, 36, 189– 197, DOI: 10.1161/ATVBAHA.115.306777
12. Wong, P. C.; Seiffert, D.; Bird, J. E.; Watson, C. A.; Bostwick, J. S.; Giancarli, M.; Allegretto, N.; Hua, J.; Harden, D.; Guay, J.; Callejo, M.; Miller, M. M.; Lawrence, R. M.; Banville, J.; Guy, J.; Maxwell, B. D.; Priestley, E. S.; Marinier, A.; Wexler, R. R.; Bouvier, M.; Gordon, D. A.; Schumacher, W. A.; Yang, J. Blockade of Protease-Activated Receptor-4 (PAR4) Provides Robust Antithrombotic Activity with Low Bleeding. *Sci. Transl. Med.* 2017, 9, eaaf5294 DOI: 10.1126/scitranslmed.aaf5294
13. Dockendorff, C.; Aisiku, O.; Verplank, L.; Dilks, J. R.; Smith, D. A.; Gunnink, S. F.; Dowal, L.; Negri, J.; Palmer, M.; Macpherson, L.; Schreiber, S. L.; Flaumenhaft, R. Discovery of 1,3-Diaminobenzenes as Selective Inhibitors of Platelet Activation at the PAR1 Receptor. *ACS Med. Chem. Lett.* 2012, 3, 232– 237, DOI: 10.1021/ml2002696
14. De Ceunynck, K.; Peters, C. G.; Jain, A.; Higgins, S. J.; Aisiku, O.; Fitch-Tewfik, J. L.; Chaudhry, S. A.; Dockendorff, C.; Parikh, S. M.; Ingber, D. E.; Flaumenhaft, R. PAR1 Agonists Stimulate APC-Like Endothelial Cytoprotection and Confer Resistance to Thromboinflammatory Injury. *Proc. Natl. Acad. Sci. U. S. A.* 2018, 115, E982– E991, DOI: 10.1073/pnas.1718600115
15. Gandhi, D. M.; Majewski, M. W.; Rosas, R.; Kentala, K.; Foster, T. J.; Greve, E.; Dockendorff, C. Characterization of Protease-Activated Receptor (PAR) Ligands: Parmodulins Are Reversible

- Allosteric Inhibitors of PAR1-Driven Calcium Mobilization in Endothelial Cells. *Bioorg. Med. Chem.* 2018, 26, 2514– 2529, DOI: 10.1016/j.bmc.2018.04.016
16. Portoghese, P. S.; Ronsisvalle, G.; Larson, D. L.; Yim, C. B.; Sayre, L. M.; Takemori, A. E. Opioid Agonist and Antagonist Bivalent Ligands as Receptor Probes. *Life Sci.* 1982, 31, 1283– 1286, DOI: 10.1016/0024-3205(82)90362-9
 17. Shonberg, J.; Scammells, P. J.; Capuano, B. Design Strategies for Bivalent Ligands Targeting GPCRs. *ChemMedChem* 2011, 6, 963– 974, DOI: 10.1002/cmdc.201100101
 18. Hiller, C.; Kühhorn, J.; Gmeiner, P. Class a G-Protein-Coupled Receptor (GPCR) Dimers and Bivalent Ligands. *J. Med. Chem.* 2013, 56, 6542– 6559, DOI: 10.1021/jm4004335
 19. Daniels, D. J.; Lenard, N. R.; Etienne, C. L.; Law, P.-Y.; Roerig, S. C.; Portoghese, P. S. Opioid-Induced Tolerance and Dependence in Mice Is Modulated by the Distance Between Pharmacophores in a Bivalent Ligand Series. *Proc. Natl. Acad. Sci. U. S. A.* 2005, 102, 19208– 19213, DOI: 10.1073/pnas.0506627102
 20. Xu, L.; Josan, J. S.; Vagner, J.; Caplan, M. R.; Hruby, V. J.; Mash, E. A.; Lynch, R. M.; Morse, D. L.; Gillies, R. J. Heterobivalent Ligands Target Cell-Surface Receptor Combinations in Vivo. *Proc. Natl. Acad. Sci. U. S. A.* 2012, 109, 21295– 21300, DOI: 10.1073/pnas.1211762109
 21. Lensing, C. J.; Adank, D. N.; Wilber, S. L.; Freeman, K. T.; Schnell, S. M.; Speth, R. C.; Zarth, A. T.; Haskell-Luevano, C. A Direct in Vivo Comparison of the Melanocortin Monovalent Agonist Ac-His-DPhe-Arg-Trp-NH₂ Versus the Bivalent Agonist Ac-His-DPhe-Arg-Trp-PEDG₂₀-His-DPhe-Arg-Trp-NH₂: a Bivalent Advantage. *ACS Chem. Neurosci.* 2017, 8, 1262– 1278, DOI: 10.1021/acscchemneuro.6b00399
 22. Hübner, H.; Schellhorn, T.; Gienger, M.; Schaab, C.; Kaindl, J.; Leeb, L.; Clark, T.; Möller, D.; Gmeiner, P. Structure-Guided Development of Heterodimer-Selective GPCR Ligands. *Nat. Commun.* 2016, 7, 12298, DOI: 10.1038/ncomms12298
 23. Shi, X.; Gangadharan, B.; Brass, L. F.; Ruf, W.; Mueller, B. M. Protease-Activated Receptors (PAR1 and PAR2) Contribute to Tumor Cell Motility and Metastasis. *Mol. Cancer Res.* 2004, 2, 395– 402
 24. Jaber, M.; Maoz, M.; Kancharla, A.; Agranovich, D.; Peretz, T.; Grisaru-Granovsky, S.; Uziely, B.; Bar-Shavit, R. Protease-Activated-Receptor-2 Affects Protease-Activated-Receptor-1-Driven Breast Cancer. *Cell. Mol. Life Sci.* 2014, 71, 2517– 2533, DOI: 10.1007/s00018-013-1498-7
 25. Kancharla, A.; Maoz, M.; Jaber, M.; Agranovich, D.; Peretz, T.; Grisaru-Granovsky, S.; Uziely, B.; Bar-Shavit, R. PH Motifs in PAR1&2 Endow Breast Cancer Growth. *Nat. Commun.* 2015, 6, 8853, DOI: 10.1038/ncomms9853
 26. Sevigny, L. M.; Austin, K. M.; Zhang, P.; Kasuda, S.; Koukos, G.; Sharifi, S.; Covic, L.; Kuliopulos, A. Protease-Activated Receptor-2 Modulates Protease-Activated Receptor-1-Driven Neointimal Hyperplasia. *Arterioscler., Thromb., Vasc. Biol.* 2011, 31, e100– e106, DOI: 10.1161/ATVBAHA.111.238261
 27. Zhang, H.-C.; Derian, C. K.; Andrade-Gordon, P.; Hoekstra, W. J.; McComsey, D. F.; White, K. B.; Poulter, B. L.; Addo, M. F.; Cheung, W.-M.; Damiano, B. P.; Oksenberg, D.; Reynolds, E. E.; Pandey, A.; Scarborough, R. M.; Maryanoff, B. E. Discovery and Optimization of a Novel Series of Thrombin Receptor (PAR-1) Antagonists: Potent, Selective Peptide Mimetics Based on Indole and Indazole Templates. *J. Med. Chem.* 2001, 44, 1021– 1024, DOI: 10.1021/jm000506s
 28. Chieng-Yane, P.; Bocquet, A.; Letienne, R.; Bourbon, T.; Sablayrolles, S.; Perez, M.; Hatem, S. N.; Lompre, A.-M.; Le Grand, B.; David-Dufilho, M. Protease-Activated Receptor-1 Antagonist F 16618 Reduces Arterial Restenosis by Down-Regulation of Tumor Necrosis Factor Alpha and

- Matrix Metalloproteinase 7 Expression, Migration, and Proliferation of Vascular Smooth Muscle Cells. *J. Pharmacol. Exp. Ther.* 2011, 336, 643– 651, DOI: 10.1124/jpet.110.175182
29. Boire, A.; Covic, L.; Agarwal, A.; Jacques, S.; Sherifi, S.; Kuliopulos, A. *PAR1 Is a Matrix Metalloprotease-1 Receptor That Promotes Invasion and Tumorigenesis of Breast Cancer Cells. Cell* 2005, 120, 303– 313, DOI: 10.1016/j.cell.2004.12.018
30. Kaufmann, R.; Rahn, S.; Pollrich, K.; Hertel, J.; Dittmar, Y.; Hommann, M.; Henklein, P.; Biskup, C.; Westermann, M.; Hollenberg, M. D.; Settmacher, U. Thrombin-Mediated Hepatocellular Carcinoma Cell Migration: Cooperative Action via Proteinase-Activated Receptors 1 and 4. *J. Cell. Physiol.* 2007, 211, 699– 707, DOI: 10.1002/jcp.21027
31. Kaufmann, R.; Mussbach, F.; Henklein, P.; Settmacher, U. Proteinase-Activated Receptor 2-Mediated Calcium Signaling in Hepatocellular Carcinoma Cells. *J. Cancer Res. Clin. Oncol.* 2011, 137, 965– 973, DOI: 10.1007/s00432-010-0961-1
32. Damiano, B. P.; Derian, C. K.; Maryanoff, B. E.; Zhang, H.-C.; Gordon, P. A. RWJ-58259: a Selective Antagonist of Protease Activated Receptor-1. *Cardiovasc. Drug Rev.* 2003, 21, 313– 326, DOI: 10.1111/j.1527-3466.2003.tb00124.x
33. Farmer, L. J.; Lessard, S.; Liu, B.; St-Onge, M.; Sturino, C.; Szychowski, J.; Yannopoulos, C. *Imidazopyridazines Useful as Inhibitors of the PAR-2 Signaling Pathway.* WO 2015/048245.
34. Krishnamurthy, V. M.; Semetey, V.; Bracher, P. J.; Shen, N.; Whitesides, G. M. Dependence of Effective Molarity on Linker Length for an Intramolecular Protein–Ligand System. *J. Am. Chem. Soc.* 2007, 129, 1312– 1320, DOI: 10.1021/ja066780e
35. Meldal, M.; Tornøe, C. W. Cu-Catalyzed Azide–Alkyne Cycloaddition. *Chem. Rev.* 2008, 108, 2952– 3015, DOI: 10.1021/cr0783479
36. Chan, T. R.; Hilgraf, R.; Sharpless, K. B.; Fokin, V. V. Polytriazoles as Copper(I)-Stabilizing Ligands in Catalysis. *Org. Lett.* 2004, 6, 2853– 2855, DOI: 10.1021/ol0493094
37. Cheng, R. K. Y.; Fiez-Vandal, C.; Schlenker, O.; Edman, K.; Aggeler, B.; Brown, D. G.; Brown, G. A.; Cooke, R. M.; Dumelin, C. E.; Doré, A. S.; Geschwindner, S.; Grebner, C.; Hermansson, N.-O.; Jazayeri, A.; Johansson, P.; Leong, L.; Prihandoko, R.; Rappas, M.; Soutter, H.; Snijder, A.; Sundström, L.; Tehan, B.; Thornton, P.; Troast, D.; Wiggin, G.; Zhukov, A.; Marshall, F. H.; Dekker, N. Structural Insight Into Allosteric Modulation of Protease-Activated Receptor 2. *Nature* 2017, 545, 112– 115, DOI: 10.1038/nature22309
38. Corbeil, C. R.; Englebienne, P.; Moitessier, N. Docking Ligands Into Flexible and Solvated Macromolecules. 1. Development and Validation of FITTED 1.0. *J. Chem. Inf. Model.* 2007, 47, 435– 449, DOI: 10.1021/ci6002637
39. Jiang, Y.; Yau, M.-K.; Lim, J.; Wu, K.-C.; Xu, W.; Suen, J. Y.; Fairlie, D. P. A Potent Antagonist of Protease-Activated Receptor 2 That Inhibits Multiple Signaling Functions in Human Cancer Cells. *J. Pharmacol. Exp. Ther.* 2018, 364, 246– 257, DOI: 10.1124/jpet.117.245027
40. Jimenez-Vargas, N. N.; Pattison, L. A.; Zhao, P.; Lieu, T.; Latorre, R.; Jensen, D. D.; Castro, J.; Aurelio, L.; Le, G. T.; Flynn, B.; Herenbrink, C. K.; Yeatman, H. R.; Edgington-Mitchell, L.; Porter, C. J. H.; Halls, M. L.; Canals, M.; Veldhuis, N. A.; Poole, D. P.; McLean, P.; Hicks, G. A.; Scheff, N.; Chen, E.; Bhattacharya, A.; Schmidt, B. L.; Brierley, S. M.; Vanner, S. J.; Bunnett, N. W. Protease-Activated Receptor-2 in Endosomes Signals Persistent Pain of Irritable Bowel Syndrome. *Proc. Natl. Acad. Sci. U. S. A.* 2018, 115, E7438–E7447, DOI: 10.1073/pnas.1721891115