



HAL
open science

Mechanical GPCR activation by traction forces exerted on receptor N-glycans

Mark G H Scott, Stefano Marullo, Stéphane Doly, Kusumika Saha, Hervé Enslen, Mark George Hunter Scott, Mathieu Coureuil

► **To cite this version:**

Mark G H Scott, Stefano Marullo, Stéphane Doly, Kusumika Saha, Hervé Enslen, et al.. Mechanical GPCR activation by traction forces exerted on receptor N-glycans. *ACS Pharmacology & Translational Science*, 2020, 10.1021/acsptsci.9b00106 . hal-02493908

HAL Id: hal-02493908

<https://hal.science/hal-02493908v1>

Submitted on 28 Feb 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Mechanical GPCR activation by traction forces exerted on receptor N-glycans

Stefano Marullo^{1*}, Stephane Doly², Kusumika Saha¹, Hervé Enslin¹, Mark G.H. Scott¹, Mathieu Coureuil³

1. Université de Paris, Institut Cochin, Inserm U1016, CNRS UMR8104, Paris, France

2. Université Clermont Auvergne, INSERM, NEURO-DOL, 63000, Clermont-Ferrand, France

3. Université de Paris, Institut-Necker-Enfants-Malades, Inserm U1151, CNRS UMR 8253, Paris, France

*Correspondence: stefano.marullo@inserm.fr (S. Marullo).

Keywords

Mechanosensors, mechanotransduction, shear stress, pilins, lectins, sialic acid, host-pathogen.

Abstract

Cells are sensitive to chemical stimulation, which is converted into intracellular biochemical signals by the activation of specific receptors. Mechanical stimulations can also induce biochemical responses via the activation of various mechanosensors. Although principally appreciated for their chemosensory function, G protein-coupled receptors (GPCRs) may participate in mechano-transduction. They are indirectly activated by the paracrine release of chemical compounds secreted in response to mechanical stimuli, but they might additionally behave as mechanosensors that are directly stimulated by mechanical forces. Although several studies are consistent with this latter hypothesis, the molecular mechanisms of a potential direct mechanical activation of GPCRs have remained elusive until recently. In particular, investigating the activation of the catecholamine β_2 -adrenergic receptor by a pathogen revealed that traction forces directly exerted on the N-terminus of the receptor via N-glycan chains activate specific signaling pathways. These findings open new perspectives in GPCR biology and pharmacology since most GPCRs express N-glycan chains in their N-terminus, which might similarly be involved in the interaction with cell surface glycan-specific lectins in the context of cell-to-cell mechanical signaling.

Mechanical stimuli acting at the level of organs, tissues, individual cells or molecular complexes regulate multiple physiological and developmental processes. Mechano-transduction, the molecular process converting mechanical stimuli into biochemical signals, is elicited by the direct activation of mechano-sensors, which are the molecules that directly respond to changes in mechanical cues. Different types of plasma membrane-associated mechano-sensors have been identified, which respond to various types of mechanical stimuli and activate distinct signaling pathways.

“Typical” mechano-sensors

The most extensively investigated mechano-sensors so far do not belong to the GPCR family. Extracellular matrix (ECM) stiffness provides mechanical signals regulating cell differentiation, proliferation, migration, apoptosis¹⁻⁴. Rigidity sensing involves transmembrane integrin molecules that bind the ECM at their extracellular side, and the actin cytoskeleton, via adapter proteins, at their intracellular side⁽⁵ for a recent review). Platelet endothelial cell adhesion molecule (PECAM)-1 present on adherent junctions forms a mechano-sensory complex⁶ with VE-cadherin and vascular endothelial growth factor receptor (VEGFR)-2/VEGFR3. In endothelial cells this complex is activated by shear stress resulting in the phosphorylation of PECAM-1 and Src-dependent activation of phosphatidylinositol-4,5-bisphosphate 3-kinase (PI3K). This process in turn activates integrins to bind to ECM by an inside-out mechanism. Piezo family mechanically-activated ion channels^{7,8} play a major role in vascular development and function, pulmonary function and sensory transduction (reviewed in⁹). In mammals, two distinct genes code for PIEZO1, principally expressed in non-neuronal cells, and PIEZO2, restricted to sensory neurons and mechano-sensory structures. These proteins are arranged as trimers. Their activation results in an influx of Na⁺ and Ca²⁺. Membrane stretching and shear stress activate PIEZOs by generating a membrane tension, which causes the reorganization of lipids around the protein and channel opening¹⁰. Additional types of mechanically-activated ions channels have been discovered in lower organisms and in mammals¹¹. Among these, two-pore-domain potassium channels (K_{2P}) constitute a family of 15 members sharing a 4 trans-membrane (TM) domain topology. Some of them directly sense mechanical forces imparted through the lipid membrane¹². Mechano-transduction also plays an important role in adaptive immune response.

Properly applied mechanical forces provide a direct synergistic activation of $\alpha\beta$ T-cell receptors (TCR), which have established a chemical bond with an antigenic peptide ligand bound to major histocompatibility complex (MHC) molecules. These forces reduce by orders of magnitude the number of peptide-bound MHC molecules sufficient to trigger a Ca^{2+} flux in T cells ¹³.

GPCR participation in mechano-transduction

Although principally known for their chemosensory function, which converts the signals conveyed by chemical ligands into intracellular biochemical signals, G protein-coupled receptors (GPCRs) can be involved in mechano-transduction (Table 1). However, although the participation of GPCRs in the transmission of external mechanical stimuli has been known for more than 25 years ¹⁴, experimental evidence that mechanical forces can directly activate these receptors has only recently emerged.

Since the discovery that stretch-induced hypertrophy of cardiac myocytes was caused by autocrine release of angiotensin II (Ang II) and subsequent activation of Ang II receptors ¹⁴, several GPCRs of smooth muscle cells were reported to be activated by the paracrine release of peptides, lipids, nucleotides and amines by endothelial cells in response to vascular stretch. In turn, the activated receptors stimulated their cognate G proteins such as G_s , $G_{q/11}$ or $G_{12/13}$ to generate a myogenic tone ¹⁵⁻¹⁷. Other investigations revealed that mechanical stimuli could also activate GPCRs without the involvement of their cognate agonists ¹⁸⁻²⁰, but the molecular mechanism of receptor activation has remained elusive in most cases. The hypothesis that GPCRs might themselves be mechano-sensors has been raised by several studies, in which GPCR conformational changes consistent with receptor activation, productive G protein coupling and β -arrestin recruitment, were documented in response to mechanical stimuli ¹⁹. Supporting this hypothesis further, it was observed that mechanical perturbation of the plasma membrane (caused by shear stress, hypotonic stress, or membrane fluidizing agents) elicited real time ligand-independent conformational transitions of GPCRs ²⁰. A large-scale automated screening assay was conducted with a mechano-sensitive cell line that exhibits shear stress-activated calcium transients to identify shear stress-sensitive mechano-transducers ²¹. With this assay and complementary gain- or loss-of-function experiments the authors found that GPR68, a $G_{q/11}$ -coupled receptor expressed in

endothelial cells of small diameter vessels, was necessary and sufficient for shear stress responses in these cells. Although satisfying all criteria for a mechano-sensor (*i.e.* essential for immediate response in mechano-sensitive cells, which naturally express the receptor and responsive to the relevant mechanical stimuli when expressed in heterologous cells) it could not be formally established whether GPR68 is directly activated by mechanical forces or by a putative upstream mechano-sensor or by the local release of protons, which were also reported to activate this GPCR.

Evidence that a mechanical stimulus can directly activate a GPCR also comes from studies on receptors belonging to a special sub-family of GPCRs, namely adhesion GPCRs (aGPCRs, see ^{22,23} for recent reviews). aGPCRs possess a long extracellular N-terminus with adhesive properties that anchors the receptor to the extracellular matrix or to opposed cell surfaces via cognate ligands. They also contain a juxta-membrane GPCR auto-proteolysis-inducing (GAIN) domain, which during protein maturation catalyzes receptor cleavage in N and C-terminal fragments (NTF and CTF) that remain non-covalently associated. aGPCRs function as adhesion molecules due to the NTF and as classical GPCRs through the CTF. Receptor activation exposes a cryptic tethered agonist ligand that activates the receptor. The latrophilin/dCIRL aGPCR, for example, is found in mechano-sensory neurons of *Drosophila* chordotonal organs and modulates ionotropic receptor currents. Whereas auto-proteolysis of the GAIN domain is not essential for dCIRL activity, the authors found that progressive lengthening of dCIRL's N-terminal fragment gradually reduces mechano-sensory neuronal responses. These findings are consistent with a model in which mechanical tension applied to the receptor determines the extent of its activity ²⁴.

A different mechanism of mechanical GPCR activation has been reported in a very recent article investigating the activation of endothelial histamine H₁ receptors (H₁Rs) by shear stress and membrane stretch ²⁵. Mechanical activation of H₁Rs was found to be agonist-independent, insensitive to inverse agonists, and G_{11/q} protein dependent, resulting in NO production. Conformational changes promoted by shear stress and stretch were distinct from those elicited by receptor agonists. Interestingly, the mechanically activated pathway was strictly dependent on the presence of an 8th helix (H8) in the C-terminal tail of the receptor: transfer of the H8 to non-responsive GPCRs conferred mechano-sensitivity to non-responsive GPCRs, whereas H8

removal in H1Rs abolished it. These observations suggest that the mechanical elongation of H8 would activate the G protein.

GPCR activation by pathogen pulling on N-terminal glycan chains

Meningococcus (*N. meningitidis*) is a human-specific Gram-negative bacterium, which colonizes the mucosa of nose and pharynx. However, when meningococci enter into the bloodstream, they rapidly spread and become pathogenic. After blood brain barrier crossing they can invade meninges, causing cerebrospinal meningitis ²⁶. When bacterial load is high, infection spreads to peripheral vessels causing septic shock, the most severe life-threatening form being *purpura fulminans* ²⁷. The interaction of the pathogen with endothelial cells initiates peripheral vascular lesions ²⁸ and is responsible for the opening of the blood brain barrier ²⁹. This interaction involves long bacterial filamentous organelles known as Type IV pili (Tfp), which mediate the adhesion of virulent capsulated meningococci to endothelial cells *in vitro* and *in vivo* ^{29,30}. Tfp interact with two host cell receptors. The first is CD147, an IgG-family single TM receptor, which does not transduce any signal but that is essential for early adhesion of bacteria to the endothelial cells ³¹. The second is a GPCR, the catecholamine β_2 -adrenergic receptor (β_2 AR). Interaction of Tfp with the N-terminus of the β_2 AR induces an allosteric beta-arrestin (β arr)-biased signalling cascade in host endothelial cells, which is not blocked by the antagonist propranolol ³². Although the G_s /cAMP pathway is not affected upon bacterial binding to endothelial cells, bacteria induce a GRK-dependent recruitment of β arrs, leading to the activation of ERK and Src, and the subsequent recruitment under bacterial colonies of various cytoskeletal (actin and ezrin) and junctional proteins. Interestingly, all these signalling events are necessary for two essential processes of meningococcus pathophysiology, namely the stabilization of growing bacterial colonies under blood-flow ³³ and the opening of endothelial junctional spaces, which become loose and ultimately allow bacteria to penetrate into tissues ³⁴, such as meninges. The interaction of the pathogen with these two distinct receptors is facilitated by the fact that the β_2 AR and CD147 are pre-assembled in endothelial cells forming heteromeric structures stabilized by the cytoskeletal protein alpha-actinin-4 ³⁵. Although these studies well outlined the principal pathophysiological events permitting meningococcus to penetrate into meninges, a major issue remained unresolved for

several years, namely how a GPCR activated by non-soluble bacterial proteins is able to transduce a signalling cascade, which is usually induced by cognate receptor ligands.

Besides their passive “hooking” role, Tfp also generate mechanical forces. Studies in *Neisseria* species demonstrated that pilus retraction driven by the bacterial ATPase PilT produces forces *in vivo* that allow bacteria to move over surfaces^{36,37}. Moreover, bacteria growing on the endothelial cell surface are constantly submitted to forces produced by blood flow, which can be propagated to endothelial cell plasma membranes via Tfp attachment. Although Tfp binding to host endothelial cells is necessary to engender pulling forces, the molecular plasma membrane tether involved in this process remained elusive. Studies recapitulating the hemodynamic conditions existing in capillaries, showed that the β_2 AR is involved in the signaling cascade that allows small meningococcal colonies to remain stable under flow³². A possible mechanistic explanation of the above findings would be that the β_2 AR is simultaneously a mechano-sensor and a transducing receptor for meningococcal Tfp.

The hypothesis that the β_2 AR is a mechano-sensor for Tfp-mediated traction was confirmed recently and represents the first demonstration that a “classical GPCR” can directly be activated by mechanical forces³⁸.

In the attempt of characterizing the binding site of pilins on the β_2 AR, a chimeric receptor approach with the angiotensin II receptor AT1R was used in a fully controlled reconstitution cell system. AT1R, also present in endothelial cells, is incompetent for *N. meningitidis* signaling. Substituting its N-terminal region with that of the human β_2 AR generated a chimera, which could be activated by *N. meningitidis in vitro*, suggesting that pilin binding to the β_2 AR N-terminus is sufficient to mediate β arr-biased activation³². Direct binding of purified pilins to this receptor region, consisting of 27 amino-acid residues, was subsequently demonstrated by homogeneous time-resolved FRET. Although only humans are infected by *N. meningitidis*²⁶, this region is conserved in mammals and is almost identical between human and monkeys. Moreover, whereas human HEK-293 cells reconstituted with mouse β_2 AR could be activated by meningococcus, mouse 3T3 cells and mouse C166 endothelial cells expressing exogenous human β_2 AR were not activated by the bacterium. These data indicated that the capacity of *N. meningitidis* to bind and activate the β_2 AR in human cells involves human host cell-specific post-translational

modification of the receptor. The β_2 AR displays two asparagine-branched glycan chains in its N-terminus³⁹. It was then investigated whether these glycans might be involved in receptor activation by meningococcus. Alanine substitution of either Asn residue reduced signaling under meningococcal colonies to control levels. In a gain-of-function strategy, two glycosylation sites, nine residues distant as in the β_2 AR, were produced by mutagenesis in the AT1R: this mutant reconstituted meningococcus-promoted signaling *in vitro*, whereas mutants expressing only one of the glycan chains (after substitution with Ala) failed. These data supported a model where both glycan chains of the β_2 AR are necessary and sufficient to permit receptor activation by *N. meningitidis*. Using a panel of lectins to inhibit meningococcus-promoted signaling *in vitro* it could be determined that terminally exposed α_{2-3} branched sialic acids play an important role in the activation of the β_2 AR by the pathogen.

This finding contributes to shed some light on the mechanism of meningococcus species selectivity. Two forms of sialic acids are predominant in mammals, Neu5Ac and Neu5Gc, which differ by a single oxygen atom⁴⁰. Only Neu5Ac is produced in humans, contrasting with the predominant presence of Neu5Gc in other mammals⁴¹. Indeed, Neu5Gc is synthesized from Neu5Ac by the cytidine monophosphate-N-acetylneuraminic acid hydrolase (CMAH)⁴², which is absent in humans, due to a mutation in the *cmah* gene. The observations above raised the hypothesis that species selectivity of *N. meningitidis* for humans might be explained by the requirement of 2 terminally exposed Neu5Ac at a particular distance³⁸. Consistently, it was found that deletion of *cmah* in mouse cells restored meningococcal signaling via the β_2 AR, while mouse β_2 AR receptor was activated by meningococci when expressed in human cells.

From the above data a plausible scenario emerged postulating that traction forces applied by bacterial Tfp bound to sialic acid residues would activate the β_2 AR (**Figure 1**). To test this hypothesis, wild type and mutant meningococci deficient in PilT activity (referred to as ΔT) were compared for their ability to induce signaling in endothelial cells (**Figure 2**). Signaling of ΔT meningococci was significantly impaired compared to wild type bacteria under basal, static conditions. Next, adherent meningococci were submitted to orbital rotation to apply a centrifugal force on bacteria. Rotation promoted signaling under meningococcus colonies both in wild

type and ΔT meningococci, but the effect was superior for wild type colonies, indicating that maximal signaling depends on added effects of PilT-induced pilus retraction and exogenous forces applied to bacteria. Interestingly, sialic acid-selective lectin-coated beads submitted to the same orbital rotation recapitulated the signaling features observed with meningococci. Traction forces specifically applied on the β_2 AR via its N-glycan chains can therefore induce β arr-biased activation and downstream ezrin recruitment independently of bacteria. Moreover, whereas meningococcal activation of the β_2 AR was strictly dependent on the presence of two glycan chains at a particular distance, probably reflecting structural constraints, such as pilin orientation or spacing within the bacterial pilus, β_2 AR mutants lacking either N-glycosylation site maintained their capacity of being activated by lectin-coated beads³⁸. Thus a force applied via a single N-glycan chain is potentially sufficient to promote the mechanical activation of a GPCR.

Recent structural and molecular studies have identified the events, which control GPCR function at the molecular level⁴³. For small molecule-activated class A GPCRs, the class to which the β_2 AR belongs to, the orthosteric binding site used by endogenous agonists to activate the receptor, is situated in the middle of the seven-transmembrane helical bundle, between the extracellular loops and the middle plane of the plasma membrane. Allosteric agonists bind to the receptor in varying positions outside the orthosteric site. For example, a small allosteric modulator of the β_2 AR was found to bind to a pocket formed by the cytoplasmic ends of TM 1, 2, 6 and 7, the intracellular loop 1 and the helix 8⁴⁴. An allosteric modulator of the M2 muscarinic receptor, instead, binds above the orthosteric site and establishes molecular interactions with the extracellular vestibule, which includes the second extracellular loop⁴⁵. The exosite for the aryloxyalkyl tail of salmeterol, a selective β_2 AR long-acting agonist was investigated in a recent study. The salmeterol tail extends toward the extracellular surface of the receptor, filling a cleft formed by amino-acid residues belonging to extracellular loops 2 and 3 and to the extracellular ends of the TM 6 and 7⁴⁶. These findings, and the observation that the orthosteric site for of peptide-activated GPCRs can involve the N-terminal region and is stabilized by extracellular loops⁴⁷, suggests a mechanism in which the traction applied via meningococcal pili bound to β_2 AR glycan chains engages the helical bundle region, through the recruitment of the N-terminal region, which creates interactions with the transmembrane core. This model is supported by the fact that

applying traction forces on the β_2 AR, via beads that are coated with lectins specific for the exposed sialic acid of receptor glycan chains, reproduces a pili-like activation

38

Conclusion and perspectives

Over the past 20 years an increasing number of observations supported the role of GPCRs in the transduction of mechanical signals. Although in most cases GPCR activation appears as a downstream event caused by the release of receptor agonists in response to the mechanical stimulation, recent studies support that GPCRs may function as direct mechanosensors and that mechanical forces can activate these receptors in different ways. In this context, the previously unreported mechanism of mechanical activation of a GPCR, involving traction forces applied on sialic-acid-terminated glycan chains, raises the question of its physiological relevance. It may suggest that there are supplementary functions for the β_2 AR in the vascular system. For instance macrophages, which adhere to and roll over endothelial cells before entering into tissues, express the sialic acid-specific sialoadhesin Siglec-1⁴⁸, which displays the same glycan specificity as Mal-I. Siglec-1 binding to β_2 AR might induce some signaling in the context of cell-to-cell interactions and/or diapedesis. More generally, most (80%) GPCRs express at least one N-glycan chain in their N-terminus. These glycan chains might similarly be involved in the interaction with cell surface lectins and allosterically activated in the context of cell-to-cell mechanical signaling. However, it is difficult at the moment to evaluate how many GPCRs could actually be activated via a traction applied on their N-glycans. For example, lectin-coated beads failed to activate the AT1R, indicating that each receptor should be tested individually for its aptitude of being directly activated by mechanical forces. Also, additional studies will be necessary to establish how a traction force exerted on its N-terminus can structurally activate a GPCR.

Acknowledgements

This article was supported by ANR-14-IFEC-0006-01, ANR-15-CE15-0002 and ANR-19-CE14-0045 grants. SM and MC are also supported by the INSERM, the CNRS, and the Université de Paris.

References

- (1) Folkman, J. and Moscona, A. (1978) Role of cell shape in growth control. *Nature* 273, 345-9.
- (2) Watt, F. M., Jordan, P. W. and O'Neill, C. H. (1988) Cell shape controls terminal differentiation of human epidermal keratinocytes. *Proc Natl Acad Sci U S A* 85, 5576-80.
- (3) Chen, C. S., Mrksich, M., Huang, S., Whitesides, G. M. and Ingber, D. E. (1997) Geometric control of cell life and death. *Science* 276, 1425-8.
- (4) Engler, A. J., Sen, S., Sweeney, H. L. and Discher, D. E. (2006) Matrix elasticity directs stem cell lineage specification. *Cell* 126, 677-89.
- (5) Wolfenson, H., Yang, B. and Sheetz, M. P. (2019) Steps in Mechanotransduction Pathways that Control Cell Morphology. *Annu Rev Physiol* 81, 585-605.
- (6) Tzima, E., Irani-Tehrani, M., Kiosses, W. B., Dejana, E., Schultz, D. A., Engelhardt, B., Cao, G., DeLisser, H. and Schwartz, M. A. (2005) A mechanosensory complex that mediates the endothelial cell response to fluid shear stress. *Nature* 437, 426-31.
- (7) Syeda, R., Florendo, M. N., Cox, C. D., Kefauver, J. M., Santos, J. S., Martinac, B. and Patapoutian, A. (2016) Piezo1 Channels Are Inherently Mechanosensitive. *Cell Rep* 17, 1739-46.
- (8) Cox, C. D., Bae, C., Ziegler, L., Hartley, S., Nikolova-Krstevski, V., Rohde, P. R., Ng, C. A., Sachs, F., Gottlieb, P. A. and Martinac, B. (2016) Removal of the mechanoprotective influence of the cytoskeleton reveals PIEZO1 is gated by bilayer tension. *Nat Commun* 7, 10366.
- (9) Murthy, S. E., Dubin, A. E. and Patapoutian, A. (2017) Piezos thrive under pressure: mechanically activated ion channels in health and disease. *Nat Rev Mol Cell Biol* 18, 771-83.
- (10) Lewis, A. H. and Grandl, J. (2015) Mechanical sensitivity of Piezo1 ion channels can be tuned by cellular membrane tension. *eLife* 4, e12088.
- (11) Ranade, S. S., Syeda, R. and Patapoutian, A. (2015) Mechanically Activated Ion Channels. *Neuron* 87, 1162-79.
- (12) Brohawn, S. G., Su, Z. and MacKinnon, R. (2014) Mechanosensitivity is mediated directly by the lipid membrane in TRAAK and TREK1 K⁺ channels. *Proc Natl Acad Sci U S A* 111, 3614-9.

- (13) Feng, Y., Brazin, K. N., Kobayashi, E., Mallis, R. J., Reinherz, E. L. and Lang, M. J. (2017) Mechanosensing drives acuity of alphabeta T-cell recognition. *Proc Natl Acad Sci U S A* 114, E8204-E13.
- (14) Sadoshima, J., Xu, Y., Slayter, H. S. and Izumo, S. (1993) Autocrine release of angiotensin II mediates stretch-induced hypertrophy of cardiac myocytes in vitro. *Cell* 75, 977-84.
- (15) Kauffenstein, G., Laher, I., Matrougui, K., Guerineau, N. C. and Henrion, D. (2012) Emerging role of G protein-coupled receptors in microvascular myogenic tone. *Cardiovasc Res* 95, 223-32.
- (16) Wang, S., Iring, A., Strilic, B., Albarran Juarez, J., Kaur, H., Troidl, K., Tonack, S., Burbiel, J. C., Muller, C. E., Fleming, I., Lundberg, J. O., Wettschureck, N. and Offermanns, S. (2015) P2Y2 and Gq/G11 control blood pressure by mediating endothelial mechanotransduction. *J Clin Invest* 125, 3077-86.
- (17) Iring, A., Jin, Y. J., Albarran-Juarez, J., Siragusa, M., Wang, S., Dancs, P. T., Nakayama, A., Tonack, S., Chen, M., Kunne, C., Sokol, A. M., Gunther, S., Martinez, A., Fleming, I., Wettschureck, N., Graumann, J., Weinstein, L. S. and Offermanns, S. (2019) Shear stress-induced endothelial adrenomedullin signaling regulates vascular tone and blood pressure. *J Clin Invest* 129, 2775-91.
- (18) Zou, Y., Akazawa, H., Qin, Y., Sano, M., Takano, H., Minamino, T., Makita, N., Iwanaga, K., Zhu, W., Kudoh, S., Toko, H., Tamura, K., Kihara, M., Nagai, T., Fukamizu, A., Umemura, S., Iiri, T., Fujita, T. and Komuro, I. (2004) Mechanical stress activates angiotensin II type 1 receptor without the involvement of angiotensin II. *Nat Cell Biol* 6, 499-506.
- (19) Mederos y Schnitzler, M., Storch, U., Meibers, S., Nurwakagari, P., Breit, A., Essin, K., Gollasch, M. and Gudermann, T. (2008) Gq-coupled receptors as mechanosensors mediating myogenic vasoconstriction. *EMBO J* 27, 3092-103.
- (20) Chachisvilis, M., Zhang, Y. L. and Frangos, J. A. (2006) G protein-coupled receptors sense fluid shear stress in endothelial cells. *Proc Natl Acad Sci U S A* 103, 15463-8.
- (21) Xu, J., Mathur, J., Vessieres, E., Hammack, S., Nonomura, K., Favre, J., Grimaud, L., Petrus, M., Francisco, A., Li, J., Lee, V., Xiang, F. L., Mainquist, J. K., Cahalan, S. M., Orth, A. P., Walker, J. R., Ma, S., Lukacs, V., Bordone,

- L., Bandell, M., Laffitte, B., Xu, Y., Chien, S., Henrion, D. and Patapoutian, A. (2018) GPR68 Senses Flow and Is Essential for Vascular Physiology. *Cell* 173, 762-75 e16.
- (22) Langenhan, T., Piao, X. and Monk, K. R. (2016) Adhesion G protein-coupled receptors in nervous system development and disease. *Nat Rev Neurosci* 17, 550-61.
- (23) Folts, C. J., Giera, S., Li, T. and Piao, X. (2019) Adhesion G Protein-Coupled Receptors as Drug Targets for Neurological Diseases. *Trends Pharmacol Sci* 40, 278-93.
- (24) Scholz, N., Guan, C., Nieberler, M., Grotemeyer, A., Maiellaro, I., Gao, S., Beck, S., Pawlak, M., Sauer, M., Asan, E., Rothmund, S., Winkler, J., Promel, S., Nagel, G., Langenhan, T. and Kittel, R. J. (2017) Mechano-dependent signaling by Latrophilin/CIRL quenches cAMP in proprioceptive neurons. *eLife* 6
- (25) Erdogmus, S., Storch, U., Danner, L., Becker, J., Winter, M., Ziegler, N., Wirth, A., Offermanns, S., Hoffmann, C., Gudermann, T. and Mederos, Y. S. M. (2019) Helix 8 is the essential structural motif of mechanosensitive GPCRs. *Nat Commun* 10, 5784.
- (26) Coureuil, M., Bourdoulous, S., Marullo, S. and Nassif, X. (2014) Invasive meningococcal disease: a disease of the endothelial cells. *Trends Mol Med* 20, 571-8.
- (27) Stephens, D. S., Greenwood, B. and Brandtzaeg, P. (2007) Epidemic meningitis, meningococcaemia, and Neisseria meningitidis. *Lancet* 369, 2196-210.
- (28) Lemichez, E., Lecuit, M., Nassif, X. and Bourdoulous, S. (2010) Breaking the wall: targeting of the endothelium by pathogenic bacteria. *Nat Rev Microbiol* 8, 93-104.
- (29) Virji, M. (2009) Pathogenic neisseriae: surface modulation, pathogenesis and infection control. *Nat Rev Microbiol* 7, 274-86.
- (30) Join-Lambert, O., Lecuyer, H., Miller, F., Lelievre, L., Jamet, A., Furio, L., Schmitt, A., Pelissier, P., Fraitag, S., Coureuil, M. and Nassif, X. (2013) Meningococcal interaction to microvasculature triggers the tissular lesions of purpura fulminans. *J Infect Dis* 208, 1590-7.
- (31) Bernard, S. C., Simpson, N., Join-Lambert, O., Federici, C., Laran-Chich, M. P., Maissa, N., Bouzinba-Segard, H., Morand, P. C., Chretien, F., Taouji, S.,

- Chevet, E., Janel, S., Lafont, F., Coureuil, M., Segura, A., Niedergang, F., Marullo, S., Couraud, P. O., Nassif, X. and Bourdoulous, S. (2014) Pathogenic *Neisseria meningitidis* utilizes CD147 for vascular colonization. *Nat Med* 20, 725-31.
- (32) Coureuil, M., Lécuyer, H., Scott, M. G. H., Boularan, C., Enslin, H., Soyer, M., Mikaty, G., Bourdoulous, S., Nassif, X. and Marullo, S. (2010) Meningococcus hijack a β 2-adrenoceptor- β -arrestin pathway to cross brain microvasculature endothelium. *Cell* 143, 1149-60
- (33) Mikaty, G., Soyer, M., Mairey, E., Henry, N., Dyer, D., Forest, K. T., Morand, P., Guadagnini, S., Prevost, M. C., Nassif, X. and Dumenil, G. (2009) Extracellular bacterial pathogen induces host cell surface reorganization to resist shear stress. *PLoS Pathog* 5, e1000314.
- (34) Coureuil, M., Mikaty, G., Miller, F., Lecuyer, H., Bernard, C., Bourdoulous, S., Dumenil, G., Mege, R. M., Weksler, B. B., Romero, I. A., Couraud, P. O. and Nassif, X. (2009) Meningococcal type IV pili recruit the polarity complex to cross the brain endothelium. *Science* 325, 83-7.
- (35) Maïssa, N., Covarelli, V., Janel, S., Durel, B., Simpson, N., Bernard, S. C., Pardo-Lopez, L., Bouzinba-Ségard, H., Faure, C., Scott, M. G. H., M., C., Morand, P. C., Lafont, F., Nassif, X., Marullo, S. and Bourdoulous, S. (2017) Strength of *Neisseria meningitidis* binding to endothelial cells requires highly-ordered CD147/ β 2-adrenoceptor clusters assembled by alpha-actinin-4. *Nat Commun* 8, 15764
- (36) Merz, A. J., So, M. and Sheetz, M. P. (2000) Pilus retraction powers bacterial twitching motility. *Nature* 407, 98-102.
- (37) Biais, N., Ladoux, B., Higashi, D., So, M. and Sheetz, M. (2008) Cooperative retraction of bundled type IV pili enables nanonewton force generation. *PLoS Biol* 6, e87.
- (38) Virion, Z., Doly, S., Saha, K., Lambert, M., Bied, C., Duke, R. M., Rudd, P. M., Robbe-Maselot, C., Nassif, X., Coureuil, M. and Marullo, S. (2019) Sialic acid-mediated mechanical activation of β 2 adrenergic receptors by bacterial pilins *Nat Commun* 10, 4752
- (39) Rands, E., Candelore, M. R., Cheung, A. H., Hill, W. S., Strader, C. D. and Dixon, R. A. (1990) Mutational analysis of beta-adrenergic receptor glycosylation. *J Biol Chem* 265, 10759-64.

- (40) Varki, A. (2001) Loss of N-glycolylneuraminic acid in humans: Mechanisms, consequences, and implications for hominid evolution. *Am J Phys Anthropol Suppl* 33, 54-69.
- (41) Varki, A. (2007) Glycan-based interactions involving vertebrate sialic-acid-recognizing proteins. *Nature* 446, 1023-9.
- (42) Kawano, T., Koyama, S., Takematsu, H., Kozutsumi, Y., Kawasaki, H., Kawashima, S., Kawasaki, T. and Suzuki, A. (1995) Molecular cloning of cytidine monophospho-N-acetylneuraminic acid hydroxylase. Regulation of species- and tissue-specific expression of N-glycolylneuraminic acid. *J Biol Chem* 270, 16458-63.
- (43) Wacker, D., Stevens, R. C. and Roth, B. L. (2017) How ligands illuminate GPCR molecular pharmacology. *Cell* 170, 414-27.
- (44) Liu, X., Ahn, S., Kahsai, A. W., Meng, K. C., Latorraca, N. R., Pani, B., Venkatakrisnan, A. J., Masoudi, A., Weis, W. I., Dror, R. O., Chen, X., Lefkowitz, R. J. and Kobilka, B. K. (2017) Mechanism of intracellular allosteric beta2AR antagonist revealed by X-ray crystal structure. *Nature* 548, 480-4.
- (45) Kruse, A. C., Ring, A. M., Manglik, A., Hu, J., Hu, K., Eitel, K., Hubner, H., Pardon, E., Valant, C., Sexton, P. M., Christopoulos, A., Felder, C. C., Gmeiner, P., Steyaert, J., Weis, W. I., Garcia, K. C., Wess, J. and Kobilka, B. K. (2013) Activation and allosteric modulation of a muscarinic acetylcholine receptor. *Nature* 504, 101-6.
- (46) Masureel, M., Zou, Y., Picard, L.-P., van der Westhuizen, E., Mahoney, J. P., Rodrigues, J. P. G. L. M., Mildorf, T. J., Dror, R. O., Shaw, D. E., Bouvier, M., Pardon, E., Steyaert, J., Sunahara, R. K., Weis, W. I., Zhang, C. and Kobilka, B. K. (2018) Structural insights into binding specificity, efficacy and bias of a β 2AR partial agonist. *Nat Chem Biol* 14, 1059-66.
- (47) Zhang, Y., Sun, B., Feng, D., Hu, H., Chu, M., Qu, Q., Tarrasch, J. T., Li, S., Sun Kobilka, T., Kobilka, B. K. and Skiniotis, G. (2017) Cryo-EM structure of the activated GLP-1 receptor in complex with a G protein. *Nature* 546, 248-53.
- (48) Varki, A. (2017) Biological roles of glycans. *Glycobiology* 27, 3-49.
- (49) Scimia, M. C., Hurtado, C., Ray, S., Metzler, S., Wei, K., Wang, J., Woods, C. E., Purcell, N. H., Catalucci, D., Akasaka, T., Bueno, O. F., Vlasuk, G. P., Kaliman, P., Bodmer, R., Smith, L. H., Ashley, E., Mercola, M., Brown, J. H.

- and Ruiz-Lozano, P. (2012) APJ acts as a dual receptor in cardiac hypertrophy. *Nature* 488, 394-8.
- (50) Busch, R., Strohbach, A., Pennewitz, M., Lorenz, F., Bahls, M., Busch, M. C. and Felix, S. B. (2015) Regulation of the endothelial apelin/APJ system by hemodynamic fluid flow. *Cell Signal* 27, 1286-96.
- (51) Wang, J., Hanada, K., Gareri, C. and Rockman, H. A. (2018) Mechanoactivation of the angiotensin II type 1 receptor induces beta-arrestin-biased signaling through Gα_q coupling. *J Cell Biochem* 119, 3586-97.
- (52) Zhang, Y. L., Frangos, J. A. and Chachisvilis, M. (2009) Mechanical stimulus alters conformation of type 1 parathyroid hormone receptor in bone cells. *Am J Physiol Cell Physiol* 296, C1391-9.
- (53) Dela Paz, N. G., Melchior, B. and Frangos, J. A. (2017) Shear stress induces Gα_q/11 activation independently of G protein-coupled receptor activation in endothelial cells. *Am J Physiol Cell Physiol* 312, C428-C37.
- (54) Jung, B., Obinata, H., Galvani, S., Mendelson, K., Ding, B. S., Skoura, A., Kinzel, B., Brinkmann, V., Rafii, S., Evans, T. and Hla, T. (2012) Flow-regulated endothelial S1P receptor-1 signaling sustains vascular development. *Dev Cell* 23, 600-10.

Table 1. GPCRs involved in mechanotransduction

Mechano-sensory Receptor/Natural ligand	Cell type	Type of mechanical activation	Outputs, mechanisms of activation	References
Adhesion GPCRs (aGPCRs): dCIRL/tether	Sensory neurons (drosophila)	Mechanical vibrations; activation of tethered large extracellular domain (ECL), not necessitating ECL proteolysis (which is typically involved in the activation of aGPCRs)	cAMP decrease in the cell, possibly due to the activation of G α i; downstream alteration of the NOMPC anion channel activity; fine tuning of neuronal response	24
APJ/apelin	Cardiomyocytes Endothelial cells	Stretch Blood flow (shear stress)	Stretch signals in an APJ- and β -arrestin dependent, G-protein-independent fashion to induce hypertrophy Hypothesis: upregulation of APJ in vascular cells is generated by the mechanosensitive properties of the receptor itself.	49 50
AT1R/angiotensin II	Cardiomyocytes, HEK293 and COS7 cells Rat aortic A7r5 cells, HEK293 cells Ventricular endothelial cells	Mechanical stretching Hypo-osmotic stretch, application of positive pressures in patch-clamp experiments Hypotonicity, membrane stretch, increased intravascular pressure stretch (left ventricle balloon stretch)	Stretch-induced hypertrophy of cardiac myocytes caused by autocrine release of Ang II Agonist-independent receptor activation (unidentified mechanism), activation of G $_{\alpha/11}$ and Jak2 Stretch-dependent, agonist-independent G $_{\alpha/11}$ activation by receptors upon antagonist-blocked conformational change (H1R>AT1R>M5R>V1AR*); secondary activation of transient receptor potential (TRP)-6 cation channel; increase of myogenic tone of vascular smooth muscle cells Coupling to G α i; G α i-dependent recruitment of β -arrestins, EGFR transactivation and ERK phosphorylation	14 18 19 51
β_2 AR catecholamines	Human brain microvasculature endothelial cells (D3 cell line); transfected cells expressing β_2 AR and β -arrestins	Shear stress (indirect) and traction of bacterial (meningococcus) pili	Traction forces directly applied on the N-terminus of the β_2 AR via a specific glycan (Neu5Ac). β -arrestin-biased activation of Src-cortactin pathways and recruitment of junctional proteins under bacterial colonies causing the opening of the intercellular spaces of endothelial cells.	38
B2R/bradykinin	Bovine aortic endothelial cells	Fluid shear stress, hypo-osmotic stimulation, increase in plasma membrane fluidity	Changes in cell membrane tension and membrane fluidity affect conformational dynamics of GPCRs (agonist independent but blocked by selective antagonists)	20 19
ET1AR/endothelin	HEK293 cells	Stretch	Stretch-dependent, agonist-independent Gq/11 activation (H1R>AT1R>M5R>V1AR*); secondary activation of transient receptor potential (TRP)-6 cation channel R	19
GPR68	MDA-MB-231 Cells (breast cancer cells used for screening); murine primary microvascular endothelial cells. GRPR is naturally expressed in endothelial cells of small diameter arteries and in immune cells	Shear stress imposed by disturbed and laminar flow. Probable role in flow mediated dilation	Direct mechanical stimulation inducing receptor conformational changes or, indirectly downstream a still unknown mechanosensor; G $_{\alpha/11}$ -coupled, PLC activation, Ca $^{++}$ release from ER stores	21
H1R/histamine	HEK293 cells Endothelial cells	Stretch, Shear Stress	Stretch-dependent, agonist-independent Gq/11 activation (H1R>AT1R>M5R>V1AR*); secondary activation of transient receptor potential (TRP)-6 cation channel Traction over helix 8	19 25
M5R/acetylcholine	HEK293 cells	Stretch	Stretch-dependent, agonist-independent Gq/11 activation (H1R>AT1R>M5R>V1AR*); secondary activation of transient receptor potential (TRP)-6 cation channel	19
PTH1R/parathormone	Bone cells, murine preosteoblastic cells (MC3T3-E1)	Fluid shear stress	Changes in conformational equilibrium of the PTH1R, inhibited by the agonist. Mimicked by membrane fluidization using benzyl alcohol or cholesterol extraction	52
Receptor-independent, S1P3-coupled G protein	Human coronary artery endothelial cells (HCAECs)	Shear stress	Association between G $_{\alpha/11}$ and PECAM-1 under basal conditions; dissociation from one another in response to shear stress; direct activation of G $_{\alpha/11}$, independent of GPCR activation (the possible role of another GPCR in heteromeric complex with S1P3 cannot be excluded)	53
SIP1/sphingosine 1-phosphate	Endothelial cells during angiogenesis	Laminar shear stress	Direct SIP1 ligand-independent activation by shear stress stabilizes blood vessels in development and homeostasis	54
V1R/vasopressin	HEK293 cells	Stretch, Shear Stress	Stretch-dependent, agonist-independent G $_{\alpha/11}$ activation (H1R>AT1R>M5R>V1AR*); secondary activation of transient receptor potential (TRP)-6 cation channel Traction over helix 8	19 25
indirect GPCR (ETRs, TXA2R, PGH2R, S1PR, P2YR,) activation by locally released ligands	Endothelial cells acting on smooth muscle cells (paracrine activation)	Vascular stretch	Myogenic tone is generated by the indirect activation of GPCRs coupled to G $_{\alpha-11}$ or G $_{12-13}$. Stimulation occurs in response to peptides, lipids, nucleotides, amines released locally by endothelial cells. Activation of actin-myosin interaction	15 16
Indirect activation of adrenomedullin R	Endothelial cells	Shear stress	PIEZO1 mediated fluid shear stress-induced release of adrenomedullin, receptor activation, Gs-dependent cAMP production, eNOS activation	17

Figure Legends

Figure 1. Chemical and mechanical activation of the β_2 AR

The β_2 AR is principally known for its chemosensory functions (right). Agonist binding (isoproterenol in the figure) to the receptor orthosteric binding pocket induces conformational changes and coupling with its cognate G_s heterotrimeric G protein. Subsequent phosphorylation by G protein receptor kinases (GRKs) and β arr recruitment extend receptor signaling to additional pathways (not shown). β arrs are also involved in the uncoupling of the β_2 AR with the G_s protein and in receptor endocytosis. Meningococcal pili (Tfp) mechanically activate the β_2 AR (left). Pilus component PilE and PilV bind to β_2 AR N-terminal glycans by interacting with terminal Neu5Ac (purple diamonds) branched on galactose residues (yellow circles). Bacteria “pull” the receptor N-terminus and induce a conformational change of the β_2 AR, which recruits β arrs without coupling with the G_s G protein. This mechanical activation can also be reproduced by beads coated with lectins that recognize Neu5Ac if beads are submitted to centrifugal forces.

Figure 2. Extrinsic and intrinsic forces concur to β_2 AR activation

Once in the blood, meningococci adhere to endothelial cells via their type-IV pili. Growing colonies at the apical surface of endothelial cells are then submitted to forces exerted by blood flow. In addition, meningococcal PilT ATPase generates traction forces via pili *in vivo* allowing bacteria to crawl over surfaces. To evaluate the respective contribution of intrinsic and extrinsic forces to the mechanical activation of the β_2 AR by meningococci, the activation of receptor signaling was compared in wild-type and PilT defective bacteria (ΔT). Human endothelial cells (hCMEC/D3 cell line) were infected with wild type or mutant bacteria and ezrin recruitment under colonies (a downstream signaling event elicited by meningococcus in host cells) was analyzed under static conditions (2h incubation) or under orbital rotation (15min after initial static incubation) aimed at applying a centrifugal force on bacteria. After cell fixation, for each experimental condition the % of colonies, which recruit ezrin was counted under a fluorescent microscope. The amount of ezrin recruitment under each colony was quantified from Apotome acquired images using Image J software (expressed as

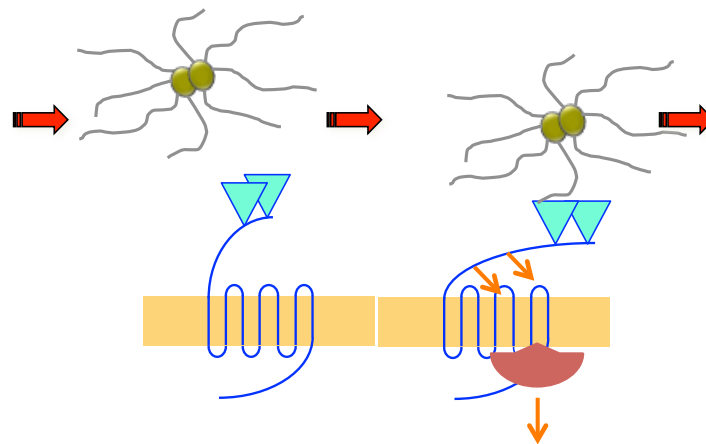
arbitrary fluorescence value per pixel). The histogram values were obtained by multiplying the % values with the median values of ezrin fluorescence.

"For Table of Contents Use Only"

Table of content graphic

Mechanical GPCR activation by traction forces exerted on receptor N-glycans

Stefano Marullo, Stephane Doly, Kusumika Saha, Hervé Enslen, Mark G.H. Scott, Mathieu Coureuil



The application of a traction force on β_2 AR glycan chains by meningococcal pili induces a distinct allosteric mode of receptor activation which recruits β -arrestin (brown) without activating the G protein. Red arrows represent the force generated by blood flow.