

International Union of Pharmacology. XXVIII. Proteinase-Activated Receptors

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Abstract—Proteinase-activated receptors (PARs) represent a unique subclass of G-protein-coupled receptors of which four family members have now been cloned from a number of species. The novel mechanism of receptor activation involves the proteolytic unmasking of a cryptic N-terminal receptor sequence that, remaining tethered, binds to and triggers receptor function. In addition, short (five to six amino acids) synthetic peptides, based on the proteolytically revealed motif, can activate PARs without the unmasking of the tethered ligand. This article summarizes the experiments leading to the pharmacological characterization and cloning of the four PAR family members and provides a

rationale for their designation by the acronym “PAR”. The ability to distinguish among the PARs pharmacologically 1) with selective proteinase activators, 2) with receptor-selective peptide agonists, and 3) with peptide and nonpeptide antagonists is discussed, as are the molecular mechanisms of receptor activation and desensitization/internalization. Finally, the potential physiological roles of the PARs, which are widely distributed in many organs in the settings of tissue injury, repair, and remodeling, including embryogenesis and oncogenesis are discussed, and the newly appreciated roles of proteinases as signaling molecules that can act as either functional agonists or antagonists are highlighted.

I. Introduction

Few receptor searches have revealed more intriguing receptor mechanisms than the one leading to the discovery

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of the receptors responsible for thrombin-mediated platelet aggregation. The search for a functional thrombin receptor, using expression cloning methods rather than the previously unsuccessful classical ligand-binding approach, led to the cloning of a G-protein-coupled receptor (Rasmussen et al., 1991; Vu et al., 1991a) that mediates the cellular actions of thrombin on platelets, endothelial cells, fibroblasts, and other cell types. The unique property of the

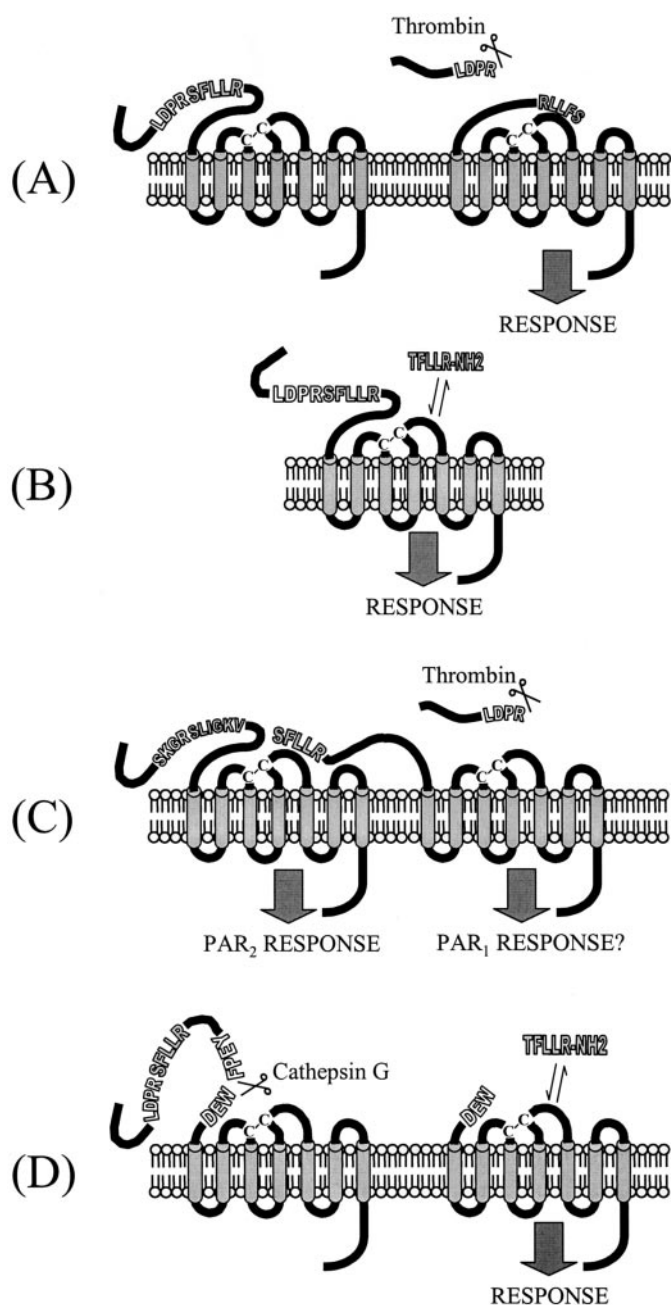


FIG 1. Mechanisms of activation and inactivation of PARs. A, the functional PARs cloned to date contain within their receptor N terminus a serine protease cleavage/activation site that, once cleaved by a serine protease, results in the unmasking of a cryptic tethered ligand sequence. The revealed tethered ligand sequence is believed to bind to and subsequently activate the receptor. The example provided (A) is for human PAR₁ activation by thrombin. B, PARs may be activated independently of proteolytic unmasking of the tethered ligand sequence by small synthetic peptides (PAR-APs) corresponding to the first five or six amino acids of the tethered ligand sequence. Activation by the receptor-selective PAR₁AP, TFLLR-NH₂, is shown. C, intermolecular activation of PAR₁ or PAR₂ may occur following PAR₁ activation, whereby the unmasked tethered ligand of a PAR₁ receptor activates an uncleaved neighboring PAR₂ or PAR₁ receptor. D, inactivation of PARs may occur by proteases cleaving the receptor C-terminally of the tethered ligand sequence, thus amputating the tethered ligand from the receptor body. These amputated receptors can no longer be activated by proteinases but are still responsive to exogenously applied PAR-APs. Note: a putative cysteine palmitoylation site in the C-terminal tail (present in all PARs except human PAR₄) may result in a fourth intracellular loop (not shown) that could play a role in receptor signaling.

thrombin receptor that distinguishes it from all other G-protein-coupled receptors relates to its lack of a “classical” circulating agonist and its unusual mechanism of triggering that involves the proteolytic unmasking of an N-terminal sequence buried in the “pro-receptor” (Fig. 1A), which then acts as a “tethered” or anchored receptor-stimulating ligand. Thus, in thinking about the proteinase-activated receptor (PAR²) family, for which the first discovered receptor for thrombin is the prototype (now designated PAR₁), it is necessary to make a paradigm shift from the perspective of all other previously known G-protein-coupled receptor systems. Remarkably, it was demonstrated (Vu et al., 1991a) that without the unmasking of its cryptic tethered ligand, PAR₁ can be activated by relatively short synthetic peptides with sequences based on that of the proteolytically revealed tethered ligand (so-called thrombin receptor-activating polypeptides, or TRAPs; now referred to as PAR-activating peptides, or PAR-APs). The TRAPs (or PAR₁APs) were used as surrogate activators of PAR₁ to evaluate the potential actions of thrombin on tissues wherein the effects of the proteinase itself might be difficult to interpret; the PAR₁APs have also served as a basis for the development of PAR₁-targeted antagonists (see below).

Results with the originally designed PAR₁APs, including peptide structure-activity studies, interspecies studies of platelet aggregation, and the development of PAR₁ knockout mice, clearly pointed to the existence of other members of the PAR family. Thus, the serendipitous discovery of a second G-protein-coupled proteinase-activated receptor that could be stimulated by trypsin, but not thrombin (PAR₂; Nystedt et al., 1994), was not entirely unexpected. PAR₂ was found not in the course of a search for additional “thrombin receptors” but as a result of screening a mouse genomic library with a bovine substance K receptor oligonucleotide probe. The discovery of PAR₂ was facilitated by the concurrent presence in the protein/nucleotide database of the sequence of PAR₁. In addition to having considerable homology with PAR₁, PAR₂ exhibited the hallmark of PAR₁ in terms of the tethered ligand mechanism for its activation by trypsin. Like PAR₁, PAR₂ can also be activated by short peptides based on the N-terminal “tethered ligand” revealed by trypsin (e.g., SLIGKLV or SLIGRL . . . from the sequences of human and rat PAR₂, respectively). Although the PAR₂-AP SLIGRL-NH₂ cannot activate PAR₁, we soon realized that the PAR₁APs originally described could activate PAR₂, and peptide structure-activity studies were required to design PAR₁APs that could selectively activate PAR₁ without activating

² Abbreviations: PAR, proteinase-activated receptor; PAR-AP, PAR-activating peptide; Cha, cyclohexylalanine; TRAP, thrombin receptor-activating peptide; NC-IUPHAR, International Union of Pharmacology Committee on Receptor Nomenclature and Drug Classification; NCBI, National Center for Biotechnology Information; NC-IUBMB, Nomenclature Committee of the International Union of Biochemistry and Molecular Biology.

TABLE 1
Proteinase-activated receptors

	PAR ₁	PAR ₂	PAR ₃	PAR ₄
IUPHAR recommended name	PAR ₁	PAR ₂	PAR ₃	PAR ₄
IUPHAR receptor code	2.1:PAR:1:PAR1:HUMAN:00	2.1:PAR:2:PAR2:HUMAN:00	2.1:PAR:3:PAR3:HUMAN:00	2.1:PAR:4:PAR4:HUMAN:00
Alternate designators	Thrombin receptor	Trypsin receptor	Thrombin receptor	Thrombin receptor
Receptor variants		F240S mutation (h)		
Amino acid composition	425 aa (h) ^a	397 aa (h)	374 aa (h)	385 aa (h)
Agonist proteinases	Thrombin > trypsin	Trypsin, tryptase, trypsin 2, matrilysin/MT-serine protease 1	Thrombin ≫ trypsin > factor	Thrombin ≡ Trypsin
Xa does	Thrombin ≡ trypsin	Factor X _a /TF/VIIa, Der p3, Der p9	Proteases cleavage but receptor does not generate a calcium signal	Cathepsin G; factors VIIa/X
Inactivating proteinases	Cathepsin G; factors VIIa/X	Unknown	Unknown	Unknown
Tethered ligand sequences	SFLLR (h), SFLLR (m,r)	SLIGKV (h), SLIGRL (m,r)	TFRGAP (h), SFNNGP (m)	GYPGQV (h), GYPGKF (m)
Subtype selective peptide agonists	TFRIFD ^b TFLLR-NH ₂	SLIGKV-NH ₂ , SLIGRL-NH ₂ <i>Trans</i> -cinnamoyl-LIGRLO-NH ₂		GYPGKF-NH ₂ ^c GYPGQV-NH ₂ ^c AYPGKF-NH ₂
Antagonists	<i>Trans</i> -cinnamoyl-parafluoro-Phe-paraguanidino-Phe-Leu-Arg-Arg-NH ₂ ^d			TRANS-cinnamoyl-YPGKF-NH ₂ ^e
Signal transduction mechanisms	Mercaptopyronyl-Phe-Cha-Arg-Lys-Pro-Lys-Pro-Asn-Asp-Lys-NH ₂ ^f Non-peptide antagonists: RWJ56110 and RWJ58259 G _{q/11} (increased IP ₃ /DAG); G _i ; G _{12/13}	— ^g	None known	— ^g
Gene/chromosome	F2R/5q13 (h) F2R/13D2 (m)	F2RL1/5q13 (h) F2RL1/13D2 (m)	F2RL2/5q13 (h) F2RL2/13D2 (m)	F2RL3/19p12 (h) F2RL3/8B3.3 (m)
NCBI accession no.	M62424 (h) L03529 (m) M81642 (r)	U34038 (h) Z48043 (m) U61373 (r)	U92971 (h) U92972 (m)	AF080214, AF055917 (h) AF080215 (m)

^a The IUPHAR receptor code is provided for each human (h) PAR, but not for murine (m), or rat (r) PARs.
^b TFRIFD is the *Xenopus* thrombin receptor tethered ligand domain (the human PAR₁ tethered ligand domain sequence, SFLLRN, activates both PAR₁ and PAR₂ receptors).
^c AYPGKF is 10 times more potent than the natural human (GYPGQV) or murine (GYPGKF) tethered ligand sequences, which are also PAR₄ selective.
^d May also act at PAR₂, as agonist; also designated BMS 200261.
^e Validated only in rat platelets.
^f Antagonizes PAR₁; acts as an agonist at PAR₂.
^g Stimulates phosphoinositide turnover through an uncharacterized G protein, probably G_{q/11}; G_i interactions with PAR₂ not evaluated; PAR₄ believed *not* to interact with G_i.

PAR₂. The availability of peptide agonists selective for PAR₁ and PAR₂ (Table 1) clarified the distinct and overlapping actions that these two receptor systems can have in a variety of tissues (see below).

However, the discovery of PAR₁ did not explain either the lack of activity of PAR₁APs in affecting rat or rabbit platelets (Kinlough-Rathbone et al., 1993) or the activity of thrombin in murine platelets that lack PAR₁ (Connolly et al., 1996). The absence of PAR₁ in murine platelets prompted a continued search for more thrombin receptors, resulting in the discovery of the third family member, PAR₃ (Ishihara et al., 1997). Yet again, when thrombin was still found to affect platelets from PAR₃ $-/-$ mice, a BLAST search of the NCBI expressed sequence tag database using the coding region of human PAR₂ was initiated, ultimately leading to the discovery of murine PAR₄ (Kahn et al., 1998). Human PAR₄ was discovered simultaneously, also as a result of a search of public and commercially available expressed sequence tag databases using human PAR 1, 2, and 3 sequences as "query" sequences (Xu et al., 1998). All of the cryptic tethered ligand sequences of the different PAR family members have turned out to be unique (Table 1). Unexpectedly, murine PAR₃ does not appear to signal itself via its thrombin-revealed sequence but, rather, acts as a cofactor for the activation of PAR₄ (see below and Nakanishi-Matsui et al., 2000). The physiological role for PAR₃ is at present somewhat of an enigma. Synthetic peptides modeled on the thrombin-revealed sequence of PAR₃ (e.g., TFRGAP. . .) do not activate murine PAR₃ but may activate both PAR₁ and PAR₂. The PAR₄ tethered ligands (murine, GYPGKF and human, GYPGQV) fail to activate other PARs but are of limited value as agonists for physiological studies because of their low potencies (active in the 100–400 μ M range). For activation of PAR₄, the more potent peptide analog, AYPGKF-NH₂, appears more promising than the parent tethered ligand sequences (Faruqi et al., 2000). Table 1 shows a number of potentially useful selective peptide agonists for the several PARs.

In summary, to date, four proteinase-activated receptors that are regulated by a proteolytically revealed tethered ligand mechanism (Fig. 1) are now known (Table 1). The PARs belong to family 1 of the G-protein-coupled superfamily of receptors, branching off from a relatedness to the neurokinin, substance P, luteinizing hor-

mone- and thyroid-stimulating hormone receptors (Vu et al., 1991a). It is the object of the sections that follow, to provide a current synopsis of the molecular pharmacology and physiology of these recently discovered receptors along with a rationale for the recommended nomenclature. Because of the novel features of this relatively new receptor family, more information will be included in this article than may be found in other IUPHAR receptor nomenclature summaries. Although many examples will be provided, the coverage is meant to be an overview rather than an all-inclusive treatise. Thus, at the outset, we offer our apologies for not citing quite a number of important contributions that were omitted in an attempt to condense the text. For more comprehensive information, the reader is referred to a number of current synopses and more exhaustive review articles (Dery et al., 1998; Coughlin, 2000; Macfarlane et al., 2001; O'Brien et al., 2001; Vergnolle et al., 2001b).

II. Nomenclature and Use of the Proteinase-Activated Receptor Designation

As pointed out under *Section I.*, the hallmark that singles out the PARs from other G-protein-coupled receptor systems is the unique proteolytic activation mechanism that reveals a cryptic amino-terminal tethered ligand. Although initially PAR₁ was termed the "thrombin receptor", it was known at the time of PAR₁ discovery (Rasmussen et al., 1991; Vu et al., 1991a) that thrombin could trigger some cell responses via a process distinct from its proteolytic activation mechanism, involving at least two different mitogenic/chemotactic peptides (thrombin-derived peptides) originating from the sequence of thrombin itself (Bar-Shavit et al., 1986; Glenn et al., 1988). This issue was initially confused further by the use of the acronym TRAP for both those peptides activating what is now termed PAR₁ (so-called PAR₁APs) and peptides that interact with the as yet unidentified receptor(s) for the thrombin-derived peptides. To render the issue of nomenclature more complex, it can be pointed out that other receptor systems, like the one for insulin, can be activated by a proteolytic mechanism that does *not* involve the unmasking of a cryptic receptor-activating ligand (reviewed briefly by Hollenberg, 1996). Thus, the term PAR, adopted by the NC-IUPHAR committee (Table 2), refers specifically to the G-protein-

TABLE 2
IUPHAR Nomenclature Committee on PARs

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coupled receptor subfamily that is activated proteolytically via a tethered ligand mechanism. The designation PAR was retained because, historically, the acronym has been widely used in the literature in a variety of fields (hematology, vascular biology, developmental biology, and neurobiology) dealing with the biological actions of thrombin and trypsin. It can be noted that, since a variety of proteinases can regulate PARs (see below and Table 1), the selected PAR abbreviation has the virtue of conveying generalized mechanistic and functional information. Furthermore, the "R" in PAR has been retained for receptor designation to avoid confusion with the acronym "PA", used frequently for the enzyme plasminogen activator. Notwithstanding, the unwary who regularly search the database with this designated "PAR" acronym will find that the abbreviation has already been claimed in a number of other fields, ranging from *Caenorhabditis elegans* genetics to prostate cancer biology. Finally, there is the unforgiving computer algorithm, which will yield a distinct database depending on whether one uses the biochemically correct definition, "proteinase", or the commonly used term "protease". Because PARs are activated by an endoproteolytic cleavage, the term "proteinase," commonly used to designate the NC-International Union of Biochemistry and Molecular Biology Nomenclature Committee-recommended term, "endopeptidase" (discussed by Barrett, 2001), is more precise to describe these receptors. In summary, the designated receptor nomenclature outlined in Table 1 for the PAR family is appropriate and in common usage for describing those receptors that possess a proteolytically activated tethered ligand mechanism, but the acronym "PAR" must be used with care for an efficient general literature search.

III. Receptor Subtypes

A. Defining Proteinase-Activated Receptor Subtypes Using Enzyme and Peptide Agonists

A traditional pharmacological approach to receptor classification (e.g., Ahlquist, 1948) did indeed point to the existence of PAR subtypes (Hollenberg et al., 1993) well before the cloning of all four currently known family members listed in Table 1. As mentioned above, the use of PAR₁APs, and thrombin itself, as receptor probes pointed to a unique set of PARs present on rodent platelets before the successful cloning of PAR₃ and PAR₄. Furthermore, upon discovery of PAR₂, it became clear that although trypsin at appropriate concentrations could activate both PAR₂ (<10 U/ml; approximately 20 nM) and PAR₁ (≥50 U/ml; >100 nM), thrombin could not activate PAR₂. Thus, pharmacologically, the PARs can be distinguished on the basis of their relative susceptibility to activation by serine proteinases (principally, thrombin and trypsin), and there is every reason to expect that the use of distinct proteinase families as probes may lead to the discovery of novel proteinase-activated receptor systems that may or may not use a

tethered ligand mechanism for activation. Apart from proteinase susceptibility, the most clear-cut molecular characteristic that distinguishes one PAR from another is the sequence of the proteolytically revealed tethered ligand (Table 1). As alluded to above, studies with peptide analogs of the PAR₁APs pointed clearly to the presence of a distinct receptor system in rat gastric and vascular tissues that turned out to be PAR₂ (Hollenberg et al., 1993; Al-Ani et al., 1995). Thus, the PAR-APs have proved to be particularly useful receptor agonist probes. It has been possible to develop peptide agonists that readily distinguish among the four receptor subtypes (Table 1) and can be used as agonists to assess the potential physiological roles that each of the four receptor systems may play in vivo (see below). That said, although such peptides can be shown to be receptor-selective in cell and tissue expression systems (e.g., see Blackhart et al., 1996; Hollenberg et al., 1999; Kawabata et al., 1999), the comparatively low potency of the PAR-APs (active in the 1–400 μM range), especially for some of the low-potency PAR₄APs (active in the 100–400 μM range), should sound a cautionary note. It is entirely feasible that such PAR-APs could, at elevated concentrations in vivo, activate receptors other than the PARs (e.g., see Roy et al., 1998). Notwithstanding, the use of selected proteinases and selective PAR-APs can serve to distinguish among the PAR subtypes cloned to date.

B. Receptor Antagonists and Receptor Subtypes

The development of receptor-selective antagonists for the PAR family has proved to be an enormous challenge. Initially, the search for antagonists was based on structure-activity studies using the sequence of human PAR₁ (SFLLRN) as a point of departure (Scarborough et al., 1992; Vassallo et al., 1992; Rasmussen et al., 1993; Ceruso et al., 1999), without any knowledge of the existence of receptor subtypes. One of the first such antagonists to be reported (Seiler et al., 1995) based on the SFLLRN motif, 3-mercaptopropionyl-Phe-Cha-Cha-Arg-Lys Pro-Asn-Asp-Lys-amide, was found to block thrombin action on human platelets at low (e.g., <0.05 U/ml) but not high concentrations, possibly because of the then unknown presence of PAR₄ on human platelets. This same compound can act as a PAR₂ agonist. A second PAR₁ peptide antagonist, *trans*-cinnamoyl-paraffluoro-Phe-paraguanidino-Phe-Leu-Arg-amide (BMS 200261, also based on the PAR₁ SFLLRN... sequence), has also been described (Bernatowicz et al., 1996), which will very likely also act as a PAR₂ agonist, since the peptide *trans*-cinnamoyl-Leu-Ile-Gly Arg-Leu-Orn-amide acts as a relatively potent activator of PAR₂ (Vergnolle et al., 1998). Interestingly, the peptide *trans*-cinnamoyl-Tyr-Pro-Gly Lys-Phe-amide, based on the murine PAR₄ tethered ligand sequence, can act as a thrombin antagonist in rat platelets (Hollenberg and Saifeddine, 2001; Ma et

al., 2001), but the ability of this peptide to block PAR₄ in other species remains to be verified.

Nonpeptide PAR₁ antagonists have also been developed based on an analysis of the molecular conformation of the PAR₁-activating peptide, SFLLRN (Ceruso et al., 1999). The screens for developing PAR₁ antagonists have used either functional assays (e.g., thrombin or PAR₁AP-mediated platelet aggregation or calcium signaling) (e.g., Andrade-Gordon et al., 1999; Barrow et al., 2001) or a ligand-binding assay (Ahn et al., 1997, 2000). Surprisingly, the functional inhibition of PAR₁ by an antagonist depends on whether a peptide or thrombin itself is used as an agonist (see below). The use of a peptide modeling approach along with a calcium signaling assay employing thrombin as an agonist led to the synthesis of the PAR₁ antagonist, RWJ56110, based on a 1,3,6-trisubstituted indole template (Andrade-Gordon et al., 1999). This compound behaves as a pure PAR₁ antagonist and blocks activation of the receptor by both thrombin and PAR₁APs. This work has led to the development of a second generation antagonist, RWJ58259, based on an indazole rather than an indole template, that has proved more favorable for use in vivo in a balloon angioplasty model of restenosis (Andrade-Gordon et al., 2001; Zhang et al., 2001). Preliminary information [summarized by Rotella (2001) and Chackalamannil (2001)] indicates that a number of other groups are also developing PAR₁ antagonists; one based on derivatives of 2-amino-4-(3,5-difluorophenyl) isoxazole, which blocks both peptide- and thrombin-induced receptor activation with IC₅₀ values in the 0.1 μM range, and another based on the natural product, himbacine, which exhibits IC₅₀ values in the 10-nM range in a ligand-binding assay. One looks forward to the complete characterization of these new PAR₁ antagonists. Thus, on the whole, it can be said that the development of selective nonpeptide antagonists for PAR₁ is still in its infancy, and it may be some time before such compounds are readily available for the routine evaluation of the role of PAR₁ in physiological processes. The development of effective antagonists for PAR₂ and PAR₄ is still

just on the horizon (Hollenberg and Saifeddine, 2001). Notwithstanding, one can predict that PAR antagonists will play a key role in defining the physiological processes that the PARs subserve in vivo.

C. Molecular Definition of Receptor Subtypes

As outlined above (*Section III.A.*), the best pharmacological distinction among the four known receptor subtypes can be made using receptor-selective PAR-APs, based on the distinct sequences of the revealed tethered ligands. However, the definitive identification of the four PAR subtypes (Table 1) has come from the cloning and sequencing of the four distinct receptors and from studies of mice in which one or other of the receptors has been genetically eliminated. Northern blot analysis has revealed the presence of all four receptor subtypes in a wide range of tissues and cells in which their physiological roles are largely unknown (Table 3). PAR₃, as mentioned above, appears to be an unusual puzzle in that murine PAR₃ does not generate a signal on its own but appears to act as a cofactor for the activation of PAR₄ (Nakanishi-Matsui et al., 2000; Sambrano et al., 2001). Whether the distinct receptor subtypes cleaved by thrombin (PAR₁, PAR₃, and PAR₄) can play independent physiological roles remains to be determined. PAR₂, activated by trypsin, tryptase, and other serine proteinases, very likely plays a role complementary to the one(s) subserved by PAR₁, PAR₃, and PAR₄ (Nystedt et al., 1994; Böhm et al., 1996b; see below). Now that the receptor subtypes can be identified by molecular probe analysis (in situ hybridization, reverse transcription-polymerase chain reaction, and site-targeted antisera), their presence and actions in a variety of tissues can be explored using both a biochemical and pharmacological approach.

IV. Molecular Aspects of Proteinase-Activated Receptor Activation

A. The Tethered Ligand Mechanism

One of the first challenges upon discovery of the PAR₁ prototype of this receptor family (Rasmussen et al., 1991; Vu et al., 1991a) was to determine its mechanism

TABLE 3
Localization and potential roles of the human proteinase-activated receptors

	PAR ₁	PAR ₂	PAR ₃	PAR ₄
Tissue distribution ^a (Northern blot analysis)	Brain, lung, heart, stomach, colon, kidney, testis	Prostate, small intestine, colon, liver, kidney, pancreas, trachea	Heart, kidney, pancreas, thymus, small intestine, stomach, lymph node, trachea	Lung, pancreas, thyroid, testis, small intestine, placenta, skeletal muscle, lymph node, adrenal gland, prostate, uterus, colon
Cellular expression	Platelets, endothelium, vascular smooth muscle, leukocytes, GI tract epithelium, fibroblasts, neurons, mast cells	Endothelium, leukocytes, GI tract epithelium and lung, airway and vascular smooth muscle, neurons, mast cells, keratinocytes, lung fibroblasts, renal tubular cells	Airway smooth muscle, platelets	Platelets, megakaryocytes
Known physiological role	Platelet activation			Platelet activation
Potential physiological roles	Pro-inflammatory, embryonic development, regulation of vascular tone	Pro-inflammatory, mediator of nociception, airway protection, regulation of vascular tone	Cofactor for PAR ₄	Platelet activation

GI, gastrointestinal.

^a Information for PAR₂, PAR₃, and PAR₄ is provided for human tissues; for PAR₁, distribution is recorded in rat tissues, for which more extensive data are available than in human tissues.

of activation. Noting the homology of the N-terminal PAR₁ sequence, LDPR⁴¹S, with the LDPRI sequence responsible for thrombin-mediated activation of protein C, Vu et al. (1991a) established arginine-41 as the main target on PAR₁ for thrombin cleavage, revealing the sequence S⁴²FLLRNPNDKYEPF. . . upstream of a hirudin-like negatively charged sequence (WEDEEKNES) that serves to increase the binding affinity of thrombin for PAR₁ via the anion-binding exosite domain of thrombin (Vu et al., 1991b). This negatively charged sequence distal to the cleavage/activation site, to which the anion-binding exosite domain of thrombin can interact, is also present in PAR₃ but is absent from either PAR₄ or PAR₂. The presence of such a negatively charged sequence may rationalize in part the selectivity of thrombin for cleaving PAR₁ and PAR₃. Vu et al. (1991a) hypothesized that the revealed sequence, SFLLR. . . , might act as an activator of the receptor. Support of this tethered ligand hypothesis, involving an intramolecular mechanism for the activation of PAR₁ by thrombin, was provided not only by discovering the platelet-activating ability of the putative revealed sequence (SFLLRNPNDKYEPF) as a soluble peptide (Vu et al., 1991a) but also by experiments showing that substitution of the putative thrombin cleavage/activation site (LPDR/S. . .) with a cleavage target sequence for enterokinase (DDDDK/S), just upstream from the postulated tethered ligand receptor-activation sequence, resulted in a receptor that could be activated by enterokinase rather than thrombin (Vu et al., 1991b). Moreover, mutating the cleavage/activation site to make it resistant to thrombin proteolysis blocked thrombin-induced receptor activation. Furthermore, in confirming the intramolecular tethered ligand mechanism, it has been demonstrated that a proteolytically revealed ligand on PAR₁ can potentially activate a neighboring PAR (Chen et al., 1994; O'Brien et al., 2000) via an intermolecular mechanism, albeit with lesser efficiency. A thoughtful summary of these intermolecular activation mechanisms for the PARs is found in the review by O'Brien et al. (2001). The tethered ligand mechanism is presumed to activate PAR₂ and PAR₄ since the synthetic peptides based on the revealed sequences are able to activate the two receptors and since for PAR₂, rendering the activation sequence resistant to trypsin cleavage blocked receptor activation (Nystedt et al., 1994). As emphasized above, this tethered ligand mechanism has become the hallmark characteristic of the receptor family. The lack of signal generation by murine PAR₃ itself, which can also be cleaved to reveal a tethered ligand, remains to be explained. It can be suggested that the revealed tethered ligand on PAR₃ may activate other PARs via an intermolecular process.

B. Structure-Activity Relationships for Receptor Activation by the Tethered Ligand Sequences

As already mentioned (*Section III.A.*), considerable work has been done to explore the structure-activity

relationships for the synthetic PAR-APs, based on the distinct tethered ligand sequences of PAR₁, PAR₂, and PAR₄ (Hollenberg et al., 1992, 1993; Scarborough et al., 1992; Vassallo et al., 1992; Natarajan et al., 1995; Faruqi et al., 2000; Maryanoff et al., 2001) (see also Table 1). Surprisingly, very short peptide sequences, only five or six amino acids in length, are sufficient to activate the PARs. Taken together, the structure-activity data obtained with PAR-APs for all of the PARs point to the key importance of the first two amino acid residues of the revealed tethered ligand sequence. For instance, an aromatic residue at position 2, e.g., phenylalanine, is required for the activity of PAR₁APs (e.g., see Natarajan et al., 1995), and a hydrophobic side chain (e.g., leucine or phenylalanine) appears to be required for the activation of PAR₂ by its tethered ligand sequence (Blackhart et al., 1996; Hollenberg et al., 1996; Maryanoff et al., 2001). Furthermore, acylating the N-terminal amino acid of a PAR-AP or merely reversing the order of the first two amino acids [e.g., FSLLR (inactive) versus SFLLR (active) for PAR₁; or LSIQRL (inactive) versus SLGIQL (active) for PAR₂] abolishes the ability of the peptides to activate the receptor but does not lead to antagonist activity. Interestingly, substituting a *trans*-cinnamoyl group for the first amino acid (serine) of either the PAR₁- or PAR₄-activating peptides (but not for PAR₂APs) leads to peptides with antagonist activity for PAR₁ and PAR₄ (Bernatowicz et al., 1996; Hollenberg and Saifeddine, 2001; Ma et al., 2001). For the PARs, one can thus envision an interaction between complementary groups on the receptor with the positively charged N-terminal amino group, along with the hydrophobic side chain of the amino acid in the second position of the revealed tethered ligand sequence. Other residues, such as a positively charged lysine or arginine group, found at position 5 of all but one (human PAR₄) of the tethered ligand sequences for mammalian PARs 1, 2, and 4 have also been found to be important for the activity of PAR-APs. That said, the tethered ligands of *Xenopus* PAR₁ (TFRIFD. . .) and human PAR₄ (GYPGQV. . .) exhibit a key hydrophobic side chain at position 2 but do not possess a positively charged side chain at position 5. Yet, these peptides are capable of activating human PAR₁ and PAR₄ (albeit with very low potency) (Gerszten et al., 1994; Nanevicz et al., 1995; Faruqi et al., 2000). In this regard, it is interesting to note that a peptide, AFLARAA, which has the hydrophobic and basic side chains of a PAR₁AP as its main features, is a PAR₁ antagonist (Pakala et al., 2000). This peptide might also affect the other PARs.

To make matters more complex, it now appears that the structural requirements for the synthetic peptide sequences acting as free peptides to activate the receptor may differ somewhat from the structure-activity relationships for comparable peptide sequences acting as receptor-tethered ligands. As one example of this situation, Oksenberg and colleagues (Blackhart et al., 2000)

found that a mutation in an extracellular domain of human PAR₁ that abrogated the ability of the PAR₁AP, SFLLRNP-amide, to activate the receptor (without abolishing the ability of the receptor to bind the peptide) surprisingly did not affect the ability of thrombin to activate the mutated receptor by revealing the same peptide sequence (SFLLRNP. . .) as a tethered ligand. A complementary approach with PAR₂ has shown that a mutation introducing a positive charge into extracellular loop 2 of PAR₂ (see below) markedly reduced the potency of PAR₂ agonists acting as free peptides (e.g., SLIGRL-amide) but had little effect on the potency of trypsin to activate the receptor by unmasking the same sequence as a tethered ligand (Al-Ani et al., 1999). Thus, the conventional thinking about structure-activity relationships in the setting of G-protein-coupled receptors that respond to blood-borne agonists or neurotransmitters (e.g., muscarinic or adrenoceptor systems) may have to be modified for the analysis of the tethered ligand proteolytically activated PAR family. The differences between the tethered ligand receptor docking mechanism and that of soluble agonists may have important implications for the design of nonpeptide PAR antagonists. In this respect, it is of interest that the PAR₁ antagonist RWJ56110 blocks receptor activation by both thrombin and PAR₁APs (Andrade-Gordon et al., 1999).

C. Receptor Domains Involved in Ligand Activation

Like all other pharmacological receptors, the PARs must perform the dual function of: 1) recognizing the activating ligand (in this case, recognition of both the activating proteinase and the revealed tethered ligand) and 2) triggering an intracellular response. Additionally, since PARs are activated by a tethered ligand that cannot diffuse away, this receptor family must also provide for a rapid shut-off/desensitization mechanism. Insight about the PAR domains involved in ligand activation have come from studies of PAR₁ chimeras (*Xenopus* PAR₁/human PAR₁ and human PAR₁/murine PAR₂) in which the sequence of extracellular loop 2 was found to confer peptide specificity for the activation of the receptor (Fig. 2). Thus, substitution of the human PAR₁ extracellular loop 2 (see Fig. 2) into *Xenopus* PAR₁ conferred on the chimeric receptor a sensitivity toward the human PAR₁AP, SFLLRN-amide, which was otherwise essentially inactive in the wild-type *Xenopus* PAR₁ (Gerszten et al., 1994; Nanevicz et al., 1995); and substitution of the extracellular loop 2 sequence of murine PAR₂ into human PAR₁ conferred on the chimeric receptor sensitivity to the PAR₂-AP, SLIGRL-amide, which does not activate human PAR₁ (Lerner et al., 1996). In addition, the data of Lerner et al. (1996) point to a possible interaction between the N-terminal extracellular domain of PAR₂ and extracellular loop 3 (see Fig. 2). Furthermore, site mutations in extracellular loop 2 have indicated the importance of the acidic residues, Glu-260

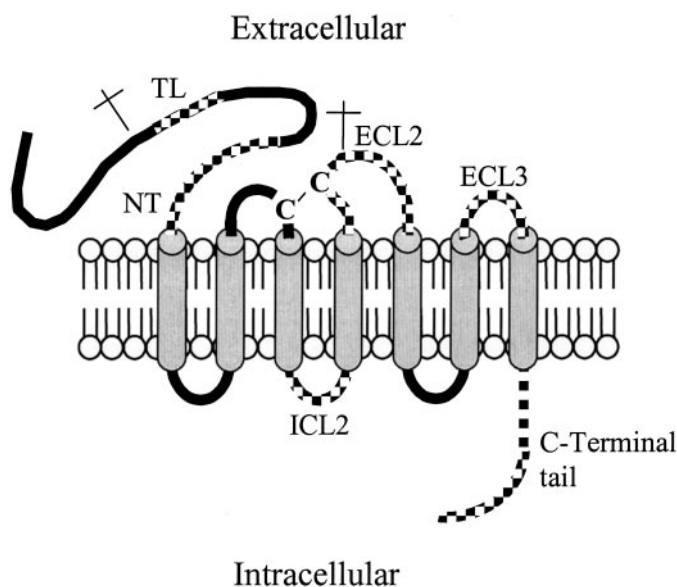


FIG 2. Schematic diagram of a PAR with domains thought to play a role in receptor signaling shown by checkering. The diagram is an amalgamation of the data obtained to date with PAR₁ and PAR₂. There is limited information on PAR₃ and PAR₄. For all of the PARs, with the exception of PAR₃, the tethered ligand (TL) is central to receptor activation following proteinase unmasking. Each tethered ligand exhibits specificity for its cognate receptor, except for PAR₁, where its TL peptide sequence also shows agonist activity toward PAR₂. For PAR₁ and PAR₂, extracellular loop 2 (ECL2) has been shown to confer PAR-AP specificity for the receptor, although the role of ECL2 for activation by the proteinase-revealed tethered ligand remains to be confirmed. For PAR₂, there is believed to be an important interaction between the N terminus (NT) and extracellular loop 3 (ECL3) in that substitution of the PAR₂ domains with comparable sequences for PAR₁, results in a loss of receptor function (Lerner et al., 1996). For PAR₁, a short region of the NT (residues 83–93), in addition to an acidic residue on extracellular loop 3, have been demonstrated to play a role in PAR-AP activation (Bahou et al., 1994; Blackhart et al., 2000). Intracellular loop 2 (ICL2) has been proposed to play a role in G-protein coupling for PAR₁ (Verrall et al., 1997), whereas the cytoplasmic tail contains phosphorylation sites that are involved in signal termination and internalization of the receptor (Trejo and Coughlin, 1999; DeFea et al., 2000). PARs possess potential N-linked glycosylation sequons (61) on their NT and ECL2. Not all potential sites of glycosylation are shown. In PAR₂, NT glycosylation has been demonstrated to regulate the ability of mast cell tryptase to activate the receptor (Compton et al., 2001).

in human PAR₁ and Glu-232/Glu-233 of rat PAR₂, for receptor activation by PAR-APs (Nanevicz et al., 1995; Al-Ani et al., 1999). It has been suggested that there may be an electrostatic interaction between these acidic groups in extracellular loop 2 and the basic arginine side chain at position 5 of the synthetic PAR-APs, providing for a “gating” or direct interaction for receptor activation (Nanevicz et al., 1995; Al-Ani et al., 1999). Other acidic groups in the extracellular domain of human PAR₁, one in loop 2 (Asp-256) and another in the third extracellular loop (Glu-347), have also been found to play a role in receptor activation by synthetic PAR-APs (Blackhart et al., 2000). Furthermore, a short amino-terminal sequence (residues 83 to 93) in human PAR₁ (but not in PAR₂) has been found to play a role in receptor activation by peptide agonists (Bahou et al., 1994; Nanevicz et al., 1995; Lerner et al., 1996). An important role for other nonacidic residues in extracellular loop 2 of PAR₂

has been heralded by the discovery of a dysfunctional polymorphic form of human PAR₂ with a phenylalanine to serine mutation at position 240 of loop 2 (Compton et al., 2000). This polymorphic receptor exhibits a reduced sensitivity to trypsin activation and an altered responsiveness to PAR-APs (Compton et al., 2000). In summary, much evidence points to a key role for extracellular loop 2 of PAR₁ and PAR₂ (and by extension, probably PAR₄) in the action of synthetic receptor-activating peptides. Whether the structural determinants for activation of this interesting extracellular domain of the PARs by synthetic peptides will be the same for activation of the receptor by the proteolytically revealed tethered ligand remains to be explored in depth. This aspect of PAR function, which is unique in comparison to other G-protein-coupled receptors, is an area that merits an extensive evaluation in the future.

D. Signaling, Desensitization, and Receptor Internalization

Once activated by their tethered ligands, the PARs produce a transient signal [e.g., a pulse of elevated intracellular calcium lasting less than 2 min or a transient effect on vascular tension (contraction or relaxation) lasting from 5 to 10 min]. This type of transient response elicited by the PARs differs from responses triggered by many other G-protein-coupled receptor systems, such as the sustained elevation of vascular tension caused by phenylephrine acting via the α -adrenoreceptor. Since, unlike other G-protein-coupled receptors, PARs are continuously exposed to the tethered ligand that cannot diffuse away, these questions arise: 1) how is the receptor rapidly desensitized? and 2) how does the cell recover its cell-surface complement of intact PARs to respond again efficiently to proteinases over time? The answer to these questions, at least insofar as PAR₁ and PAR₂ are concerned (and by extension one may include PAR₄), resides in the sequences of the intracellular receptor domains responsible for G-protein coupling (Verrall et al., 1997), receptor desensitization (Ishii et al., 1994; DeFea et al., 2000), and receptor internalization (Dery et al., 1999; Trejo and Coughlin, 1999; DeFea et al., 2000). All three of the PARs that activate an intracellular signal (PAR₁, PAR₂, and PAR₄) can cause an elevation of intracellular calcium via a presumed G_{q/11}-mediated process. For PAR₁, a role for intracellular loop 2 has been shown for G_q coupling (Verrall et al., 1997). PAR₁ (but not PAR₄; Faruqi et al., 2000) can couple not only to the G_q family, but also to the pertussis toxin-sensitive G_i (Hung et al., 1992; Swift et al., 2000) resulting in: 1) an inhibition of adenylyl cyclase and 2) presumably other processes, such as ion channel regulation and phospholipase C β and cSrc activation triggered by the G_{i α} /G_{i β} subunits (reviewed by Macfarlane et al., 2001). The coupling of PAR₁ to G_q, G_i, or both very likely depends on the cell type and the relative abundance of the two G-proteins. Evidence also suggests that PAR₁ can couple to members of the G_{12/13} family (Offermanns et al., 1994). One difficulty in interpreting

some of the data in the literature obtained before the discovery of PAR₄ is that thrombin, which can activate both PAR₁ and PAR₄ (e.g., in human platelets, where both receptors are present), was often used as an agonist rather than the receptor-selective PAR-APs. Thus, although it is clear that both PAR₁ and PAR₄ can elevate intracellular calcium, the coupling of the different PARs to other specific members of the G-protein family remains to be established unequivocally. It should be noted further that PAR₁ and PAR₄ can exhibit distinct signaling shut-off and internalization kinetics, due to distinct potential phosphorylation sites in the C-terminal domains of the two receptors (see below and Shapiro et al., 2000). Thus, the kinetics as well as the G-protein-coupling specificity among PAR₁, PAR₂, and PAR₄ will very likely be found to differ. Many of the downstream signal pathway targets that can be activated, including members of the extracellular signal-regulated kinase/mitogen-activated protein kinase/stress-activated protein kinase/c-Jun NH₂-terminal kinase family, Src-family, other tyrosine kinases, and phosphatidylinositol-3 kinase, have been well summarized in a recent review (Macfarlane et al., 2001).

The signal termination and internalization processes have so far been studied primarily for human PAR₁ and PAR₂. For both PAR₁ and PAR₂, site-targeted phosphorylation in the receptor C-terminal domain by either the G-protein-coupled receptor kinases (Krupnick and Benovic, 1998) for PAR₁ (Ishii et al., 1994; Shapiro et al., 1996; Hammes et al., 1999; reviewed by Macfarlane et al., 2001) or protein kinase C for PAR₂ (Böhm et al., 1996a), involving subsequent interactions with β -arrestin and dynamin (Dery et al., 1999; DeFea et al., 2000) plays a key role for both signal down-regulation/desensitization and receptor internalization.

The characteristics of PAR trafficking [movement from an intracellular store (in the Golgi) to the plasma membrane, and internalization and recycling] differ in a number of unique respects from the dynamics of other members of the G-protein-coupled receptor family. Unlike the β -adrenoreceptor, PAR₁ in selected cell types appears to have an intracellular reservoir from which the cell-surface receptor can be efficiently replenished via a mechanism regulated by the signaling/internalization process itself (Hein et al., 1994). This "reservoir" of PAR₁ does not appear to be present in all cell types (e.g., platelets; discussed by O'Brien et al., 2001). Furthermore, rather than being recycled to the plasma membrane after activation and internalization, as is the G-protein-coupled receptor for substance P, PAR₁ is selectively targeted to the lysosome (Trejo and Coughlin, 1999). Notwithstanding, in some cell environments, a proportion of PAR₁, cleaved and activated by thrombin, appears to become available again at the cell surface in order to still be sensitive to activation by the PAR₁AP, SFLLRN-amide (Hoxie et al., 1993; Hammes and Coughlin, 1999). These data suggest that following activation of PAR₁, the exposed tethered ligand can subse-

quently become sequestered from activating the receptor further, but the receptor at the cell surface is not desensitized to PAR₁AP activation. Such a mechanism would yet in another way distinguish PAR₁, and very likely, other active members of the PAR family, from most of the other G-protein-coupled receptor families known to date. The subtle distinctions for the desensitization/internalization and trafficking properties among PARs 1, 2, and 4 remain to be determined in detail.

E. Receptor Activation and Proteinase Susceptibility: What Are the Endogenous Proteinase-Activated Receptor Regulators?

Because of its unique "hirudin-like" thrombin-binding domain downstream of the cleavage/activation site, PAR₁ is unusually sensitive to thrombin activation compared with PAR₄. Lacking a key proline residue at the P₂ position of the cleavage/activation site, PAR₂ is not activated by thrombin at all. Nonetheless, trypsin, depending on its concentration, is able to activate signaling by all of PAR₁, PAR₂, and PAR₄, indicating susceptibility to serine proteinase cleavage at the R/S (PAR₁ and PAR₂) or G/S (PAR₄) tethered ligand activation site in the three PARs. Since there are also other basic (Lys and Arg) amino acid residues carboxy-terminal to the cleavage/activation sites of the PARs, it is not surprising that other serine proteinases can either activate [e.g., cathepsin G activation of PAR₄ (Sambrano et al., 2000); streptokinase-plasminogen activation of PAR₁ (McRedmond et al., 2000); and granzyme A activation of PAR₁/PAR₄ (Suidan et al., 1994)] or disarm the PARs by cleaving the tethered ligand domain from the receptor [e.g., cathepsin G and plasmin disarming of PAR₁ (Kuliopulos et al., 1999; Molino et al., 1995)]. In this regard, trypsin has been found both to activate and disarm PAR₁ (Kawabata et al., 1999), and a small activation of PAR₁ by plasmin can be observed (Vouret-Craviari et al., 1995; Ishihara et al., 1997) as opposed to the main disarming action of plasmin on PAR₁ (above and Kimura et al., 1996). Conceptually, the proteinases, depending on their PAR cleavage targets, can act as either functional agonists or antagonists. A further level of regulation can occur in the setting of proteinase-inhibitor production (e.g., the serpins). Therefore, an additional singular feature of the PARs, among the G-protein-coupled receptor superfamily, is that the PARs can be seen as having their own endogenous set of functional agonists and antagonists. Like PAR₁, PAR₂ can be activated by serine proteinases other than trypsin [e.g., tryptase (Molino et al., 1997), mite-derived proteinases (der p3/p9; Sun et al., 2001), and factors Xa/VIIa (Bono et al., 2000; Camerer et al., 2000)]. In principle, PAR₂, like PAR₁, could also be silenced by cleavage at a point downstream from its tethered ligand (Loew et al., 2000). The restricted activation of PAR₂ by human tryptase, which cannot fully activate glycosylated PAR₂ as does trypsin (Compton et al., 2001), illustrates a novel glycosylation-depen-

dent "control mechanism" for receptor activation that has not been observed for members of other G-protein-coupled receptor families. Whether or not glycosylation of the N-terminal domains of PAR₁ and PAR₄ will alter their susceptibility to selective activation or silencing by other proteinases remains to be determined.

For PAR₁ and PAR₄, it is clear that thrombin can play a key role as the "physiological" receptor activator. In the digestive tract, trypsin is present at concentrations sufficient for it to act as an endogenous PAR activator, depending on the local abundance of tissue-derived trypsin inhibitors (Kong et al., 1997). Furthermore, mast cell tryptase has been suggested as a potential endogenous activator of PAR₂ in humans, although the susceptibility of PAR₂ to tryptase activation *in vivo* may be restricted. That said, it is known that other members of the trypsin family capable of activating PAR₂ can be detected as proenzymes in a variety of settings [e.g., endothelial trypsinogen 2 (Koshikawa et al., 1997) that could potentially activate PAR₂ (Alm et al., 2000) and a cell-surface serine proteinase termed matriptase (Oberst et al., 2001) or membrane-type serine proteinase-1 (Takeuchi et al., 2000) that can also activate PAR₂]. Thus, as opposed to classical G-protein-coupled receptors that are activated by a select number of endogenous hormones or neurotransmitters, the PARs may be subject to both activation and inhibition (i.e., disarming) by a variety of proteinases, quite apart from the key enzymes (thrombin, trypsins, and tryptase) that are presently considered to be endogenous PAR regulators (see Table 1).

V. Physiological Roles of Proteinase-Activated Receptors

A. Thrombin Targets: Proteinase-Activated Receptors 1, 3, and 4

Quite apart from its function in the coagulation cascade, the actions of thrombin on a variety of target cells are recognized as key factors in the hemostatic and inflammatory responses to injury. Thus, many of the physiological functions of thrombin are due in large part to the actions of thrombin on platelets, endothelial cells, and leukocytes (Cirino et al., 2000; summarized by Coughlin, 2000; Macfarlane et al., 2001). Many, if not most, of these cellular responses may result from the activation of one or both PAR₁ and PAR₄. However, as pointed out above, thrombin can potentially affect cells via a noncatalytic mechanism involving its chemotactic/mitogenic peptide domains; and thrombin can also activate enzymes, such as pro-matrix metalloproteinase-2 (Lafleur et al., 2001), to affect cell behavior. Furthermore, thrombin can modulate platelet function via a glycoprotein Ib-mediated signaling mechanism that appears to act synergistically with PAR₁ and PAR₄ (Soslau et al., 2001). To distinguish between the ability of thrombin to act via the PARs as opposed to other mechanisms, it has been of enormous value 1) to use PAR-specific

agonists (e.g., TFLLR-NH₂ for PAR₁, SLIGRL-NH₂ for PAR₂, or AYPGKF-NH₂ for PAR₄); 2) to evaluate responses in PAR-deficient mice; and 3) to employ selective PAR antagonists that do not exhibit intrinsic activity (Andrade-Gordon et al., 1999; Ahn et al., 2000; Hollenberg and Saifeddine, 2001). This same kind of approach has yielded much information about the potential physiological role(s) that may be subserved by PAR₂ (see below), although a PAR₂ antagonist is not yet available. Stemming from such studies, it is clear that, as anticipated, PAR₁ plays an aggregatory and secretory role in human platelets and a role as a regulator of endothelial cell function. What might not have been predicted is that PAR₁ can also play an important role in embryonic development via its impact on endothelial cell function (Griffin et al., 2001) and in the process of restenosis after vascular injury (Andrade-Gordon et al., 2001), very likely due to PAR₁-mediated actions on vascular endothelial and smooth muscle cells. The widespread tissue distribution of PAR₁, ranging from the vasculature to the brain, lung, and gastrointestinal tract (Table 3), predicts a multifactorial role for PAR₁, including neurogenic inflammatory responses as well as cardiovascular effects (Cocks and Moffatt, 2000; de Garavilla et al., 2001; summarized by Macfarlane et al., 2001; Vergnolle et al., 2001b). That PAR₁ has been found to be an "oncoprotein" in the sense of conferring a "transformed" phenotype on NIH 3T3 cells (focus formation and anchorage- and serum-independent growth; Martin et al., 2001) and in its ability to modulate cellular invasion (Even-Ram et al., 1998, 2001; Henrikson et al., 1999; Kamath et al., 2001) adds another dimension to the potential roles that PAR₁ may play in the setting of pathophysiology.

The physiological actions of thrombin that are due to PAR₄ activation have yet to be clarified, except as a key for thrombin-mediated aggregation of human and rodent platelets (Kahn et al., 1998, 1999). Experiments with both platelets from PAR₄ $-/-$ mice (Sambrano et al., 2001) and a PAR₄ antagonist in a rat platelet preparation (Hollenberg and Saifeddine, 2001) have unequivocally established this essential role for PAR₄ in the activation of murine and rat platelets by thrombin. That cathepsin G and trypsin (and presumably, other members of the trypsin family) can also efficiently activate PAR₄ indicates that the pathophysiology of PAR₄ may well be broader than the effects of thrombin indicate. Messenger RNA for human PAR₄ has been detected in a variety of tissues, with comparatively higher amounts present in human small intestine, liver pancreas, lung, thyroid, and testis, and smaller amounts of message detected in a number of human organs, including the prostate, adrenal gland, and trachea (Xu et al., 1998; see also Table 3). The tissue distribution of PAR₄ mRNA in the mouse appears to differ from that in the human, with larger amounts found in spleen and bone marrow but relatively low expression in liver or testis

(Kahn et al., 1998). There may, therefore, be marked differences between species in the distribution of PAR₄, which will need to be taken into consideration when exploring the pharmacology of the PAR₄APs in different animals and generalizing findings obtained from one species to another. To date, the expression of PAR₄ in different tissues has not been compared with using an immunohistochemical approach. Thus, apart from its function in platelets, the diverse physiological role that PAR₄ may play represents a most interesting topic for further investigation.

The ability of thrombin to cleave PAR₃ with high efficiency and potency because of the putative interaction of the anion exosite binding domain of thrombin with the negatively charged postcleavage sequence in PAR₃ presents a puzzle, since on its own, murine PAR₃ appears not to generate an intracellular signal but rather acts as a cofactor for PAR₄ activation (Nakanishi-Matsui et al., 2000; Sambrano et al., 2001). It will be of interest to determine whether the lack of PAR₃ signaling can be attributed to special features of its intracellular domains (e.g., see Fig. 2). The wide tissue distribution (Table 3) of PAR₃ mRNA in humans, with large amounts in stomach, small intestine, and trachea, as well as in bone marrow, along with the more restricted distribution in murine tissues (splenic megakaryocytes) (Ishihara et al., 1997), presents a puzzle in terms of what the potential physiological role for PAR₃ may be.

B. Proteinase-Activated Receptor 2, a Trypsin Target

Like PAR₁, mRNA for PAR₂ can be detected in quite a number of tissues (Table 3), with strong signals observed in the gastrointestinal tract (stomach, small intestine, and colon) as well as in the kidney, with a comparable distribution in murine and human tissues (Nystedt et al., 1994; Böhm et al., 1996b). The availability of antisera that react with PAR₂ has confirmed the presence of the receptor in a large number of tissues, in parallel with the detection of receptor mRNA and, in addition, has served to localize the receptor on enteric nerves (D'Andrea et al., 1998; Corvera et al., 1999). In the absence of effective PAR₂ antagonists, it has been the use of receptor-selective PAR₂APs (e.g., SLIGRL-NH₂), along with experiments done with PAR₂ $-/-$ mice, that has provided insight as to the potential physiological role the receptor may play. To date, although the PAR₂-deficient mouse does not exhibit a distinct phenotype, the actions of the PAR₂APs suggest roles in the cardiovascular, pulmonary, and gastrointestinal systems (summarized in reviews by Cocks and Moffatt, 2000; Macfarlane et al., 2001; Vergnolle et al., 2001b), with an added intriguing impact in the setting of inflammation and nociception that involves the activation of PAR₂ on sensory nerves (Steinhoff et al., 2000; Vergnolle et al., 2001a). Evidence for a role for PAR₁ in triggering neurogenic inflammation has also been obtained (de Garavilla et al., 2001). If there is an overriding principle

that can be put forward for the physiological function of PAR₁, PAR₂, and PAR₄, one can point to their potential role in the settings of tissue injury, repair, and remodeling, including processes that take place during embryo development. In such a context, locally produced tissue proteinases, including thrombin, other enzymes in the coagulation and complement cascades, trypsin(ogens), as well as many other proteinases will undoubtedly be found to exert a key impact on tissue signaling via the PARs.

VI. Future Issues and Conclusions

With insulin and adrenaline, both known as hormones since the early part of the 20th century, knowledge of their potential physiological roles was consolidated long before their receptor mechanisms were elucidated. However, for the PARs, it would appear that the story is playing itself out in the reverse. That is, it is clear that for PAR₁, PAR₂, and PAR₄ variations on the G-protein-coupled receptor paradigm are responsible for their mechanisms of action, but the precise physiological role(s) that these receptors play, apart from the hemostatic/inflammatory/repair processes triggered by thrombin, are largely unknown. This is the more so because all of the PARs can be targets for a variety of proteolytic enzymes that can either act as surrogate receptor activators or as receptor "silencers". Thus, in a sense, the cadre of endogenous proteinases that can function as PAR regulators represents a "degenerate" agonist/antagonist "code" that sets this receptor family apart from other G-protein-coupled receptors that have a clear-cut set of endogenous agonists and few, if any, endogenous antagonists. This distinct PAR receptor paradigm is one issue that represents an intriguing challenge for future work with the PARs aimed at understanding their physiology. To this end, the use of selective PAR-targeted agonists and the development of potent PAR-targeted antagonists for all the PARs will play a key role, as will the use of PAR $-/-$ animals. It is difficult to predict the degree of "backup redundancy" that will exist for the physiological actions of the PARs, but the data available so far (e.g., the key role of endothelial PAR₁ for vascular development as opposed to PAR₂, which is also present in the endothelium) suggest that each of the PARs will be found to play a distinct physiological role. The challenge to elucidate the potential role of PAR₃ further is even more difficult since murine PAR₃ receptor, upon proteolytic cleavage, does not on its own generate an intracellular calcium signal. Furthermore, the data obtained to date also indicate that, despite similarities in G-protein coupling, quite distinct signal transduction pathways will be found to subservise each of PAR₁, PAR₂, and PAR₄. This situation is already clear in the case of the distinction between PAR₁ and PAR₄, for which one receptor (PAR₁) can signal dually via both G_q and G_i, whereas in the same

cellular context, the other receptor (PAR₄) appears unable to signal via G_i, although it does couple to G_q (Faruqi et al., 2000). Thus, another avenue that merits further exploration relates to the distinct signaling, desensitization, internalization/degradation, and recycling/replenishment processes that may occur for each of the distinct PARs. Ultimately, a most difficult question to resolve may be: what, indeed, are the endogenous PAR-regulating proteinases, and in which settings might such proteinases play a physiological role? This is a unique question, in relation to the PARs, that does not readily apply to other G-protein-coupled receptors.

Finally, there is the question as to how many more PARs there may be. Given that, to date, an extensive database search has resulted in the recent discovery of only one more member of the family (PAR₄), it may well be that other family members, if they exist, will have quite distinct sequences, even at the extracellular loop 2 locale, wherein the tripeptide sequence CHD has been found to be present in all PARs so far discovered. Alternatively, even though PAR₄ is situated on a chromosome (human 19p12; mouse 8B3.3) distinct from that of PAR₁, PAR₂, and PAR₃ (human 5q13; mouse 13D2), the presumed gene duplication giving rise to three family members tightly clustered on one chromosome may not have occurred at the site of the PAR₄ gene. Thus, at this stage in the course of PAR discovery, the number of PARs is limited to four. Notwithstanding, data obtained with the PAR-APs, using the classical pharmacological approach pioneered by Ahlquist (1948), suggest that there may be more receptors present in several tissues (endothelium and gastrointestinal tract; Roy et al., 1998; Vergnolle et al., 1998) than can be accounted for by the PARs cloned so far. As mentioned already, the receptors for these peptides may or may not turn out to be activated by proteinases. On the other hand, it is clear that a number of well known receptors (e.g., the one for insulin) can be subject to proteolytic activation, and it is quite likely that receptors yet to be discovered will be found to be targets for proteolytic activation/silencing by proteinases other than those belonging to the serine proteinase family.

In conclusion, the search for the receptor responsible for the actions of thrombin has led in a most unexpected direction, resulting in the discovery of a novel G-protein-coupled receptor family that now has four family members. The distinct mechanism of activation, via the proteolytic unmasking of a set of distinct tethered ligands for each of the PARs, clearly sets this family of receptors apart from all other G-protein-coupled receptors discovered so far. The pharmacodynamics of the PARs, including their "irreversible" mechanism of activation via a tethered ligand agonist unmasked by a triggering proteinase, have led to a shift in the conventional paradigm used to deal with agonist/receptor interactions and have put proteinases into the spotlight as signaling molecules rather than simply as enzymes responsible for enteric

digestion and remodeling extracellular matrix. The nomenclature adopted to designate this receptor family underscores the connection between the receptor family and proteinases and prompts a number of challenging future directions to determine the physiological roles these receptors and their regulatory proteinases will play. For the PARs, it can be said that the story is just at its beginning and that there are many more intriguing chapters to be written.

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REFERENCES

- Ahlquist RP (1948) A study of the adrenotropic receptors. *Am J Physiol* **153**:586–600.
- Ahn HS, Foster C, Boykow G, Arik L, Smith-Torhan A, Hesk D, and Chatterjee M (1997) Binding of a thrombin receptor tethered ligand analogue to human platelet thrombin receptor. *Mol Pharmacol* **51**:350–356.
- Ahn HS, Foster C, Boykow G, Stamford A, Manna M, and Graziano M (2000) Inhibition of cellular action of thrombin by N3-cyclopropyl-7-[[4-(1-methylethyl)phenylmethyl]-7H-pyrrolo[3, 2-f]quinazoline-1,3-diamine (SCH 79797), a nonpeptide thrombin receptor antagonist. *Biochem Pharmacol* **60**:1425–1434.
- Al-Ani B, Saifeddine M, and Hollenberg MD (1995) Detection of functional receptors for the proteinase-activated-receptor-2-activating polypeptide, SLIGRL-NH₂, in rat vascular and gastric smooth muscle. *Can J Physiol Pharmacol* **73**:1203–1207.
- Al-Ani B, Saifeddine M, Kawabata A, and Hollenberg MD (1999) Proteinase activated receptor 2: role of extracellular loop 2 for ligand-mediated activation. *Br J Pharmacol* **128**:1105–1113.
- Alm AK, Gagnemo-Persson R, Sorsa T, and Sundelin J (2000) Extrapaneatic trypsin-2 cleaves proteinase-activated receptor-2. *Biochem Biophys Res Commun* **275**:77–83.
- Andrade-Gordon P, Derian CK, Maryanoff BE, Zhang HC, Addo MF, Cheung Wm, Damiano BP, D'Andrea MR, Darrow AL, de Garavilla L, et al. (2001) Administration of a potent antagonist of protease-activated receptor-1 (PAR-1) attenuates vascular restenosis following angioplasty in rats. *J Pharmacol Exp Ther* **298**:34–42.
- Andrade-Gordon P, Maryanoff BE, Derian CK, Zhang HC, Addo MF, Darrow AL, Eckardt AJ, Hoekstra WJ, McComsey DF, Oksenberg D, et al. (1999) Design, synthesis and biological characterization of a peptide-mimetic antagonist for a tethered ligand receptor. *Proc Natl Acad Sci USA* **96**:12257–12262.
- Bahou WF, Kutok JL, Wong A, Potter CL, and Coller BS (1994) Identification of a novel thrombin receptor sequence required for activation-dependent responses. *Blood* **84**:4195–4202.
- Barrett AJ (2001) in *Proteolytic Enzymes* (Beynon R and Bond JS eds.) pp 1–21, Oxford University Press.
- Barrow JC, Nantermet PG, Selnick HG, Glass KL, Ngo PL, Young MB, Pellicore JM, Breslin MJ, Hutchinson JH, Freidinger RM, et al. (2001) Discovery and initial structure-activity relationships of trisubstituted ureas as thrombin receptor (PAR-1) antagonists. *Bioorg Med Chem Lett* **11**:2691–2696.
- Bar-Shavit R, Hruska KA, Kahn AJ, and Wilner GD (1986) Hormone-like activity of human thrombin. *Ann N Y Acad Sci* **485**:335–348.
- Bernatowicz MS, Klimas CE, Hartl KS, Peluso M, Allegretto NJ, and Seiler SM (1996) Development of potent thrombin receptor antagonist peptides. *J Med Chem* **39**:4879–4887.
- Blackhart BD, Emilsson K, Nguyen D, Teng W, Martelli AJ, Nystedt S, Sundelin J, and Scarborough R (1996) Ligand cross-reactivity within the protease-activated receptor family. *J Biol Chem* **271**:16466–16471.
- Blackhart BD, Ruslim-Litrus L, Lu CC, Alves VL, Teng W, Scarborough RM, Reynolds EE, and Oksenberg D (2000) Extracellular mutations of protease-activated receptor-1 result in differential activation by thrombin and thrombin receptor agonist peptide. *Mol Pharmacol* **58**:1178–1187.
- Böhm SK, Khitin LM, Grady EF, Aponte G, Payan DG, and Bunnett NW (1996a) Mechanisms of desensitization and resensitization of proteinase-activated receptor-2. *J Biol Chem* **271**:22003–22016.
- Böhm SK, Kong W, Bromme D, Smeekens SP, Anderson DC, Connolly A, Kahn M, Nelken NA, Coughlin SR, Payan DG, and Bunnett NW (1996b) Molecular cloning, expression and potential functions of the human proteinase-activated receptor-2. *Biochem J* **314**:1009–1016.
- Bono F, Schaeffer P, Herault JP, Michaux C, Nestor AL, Guillemot JC, and Herbert JM (2000) Factor Xa activates endothelial cells by a receptor cascade between EPR-1 and PAR-2. *Arterioscler Thromb Vasc Biol* **20**:E107–E112.
- Camerer E, Huang W, and Coughlin SR (2000) Tissue factor- and factor X-dependent activation of protease-activated receptor 2 by factor VIIa. *Proc Natl Acad Sci USA* **97**:5255–5260.
- Ceruso MA, McComsey DF, Leo GC, Andrade-Gordon P, Addo MF, Scarborough RM, Oksenberg D, and Maryanoff BE (1999) Thrombin receptor-activating peptides (TRAPs): investigation of bioactive conformations via structure-activity, spectroscopic and computational studies. *Bioorg Med Chem* **7**:2353–2371.
- Chackalamanni S (2001) Thrombin receptor antagonists as novel therapeutic targets. *Curr Opin Drug Disc Dev* **4**:417–427.
- Chen J, Ishii M, Wang L, Ishii K, and Coughlin SR (1994) Thrombin receptor activation. Confirmation of the intramolecular tethered ligand hypothesis and discovery of an alternative intermolecular liganding mode. *J Biol Chem* **269**:16041–16045.
- Cirino G, Bucci M, Cicala C, and Napoli C (2000) Inflammation-coagulation network: are serine protease receptors the knot? *Trends Pharmacol Sci* **21**:170–172.
- Cocks TM and Moffatt JD (2000) Protease-activated receptors: sentries for inflammation? *Trends Pharmacol Sci* **21**:103–108.
- Compton SJ, Cairns JA, Palmer KJ, Al-Ani B, Hollenberg MD, and Walls AF (2000) A polymorphic protease-activated receptor 2 (PAR2) displaying reduced sensitivity to trypsin and differential responses to PAR agonists. *J Biol Chem* **275**:39207–39212.
- Compton SJ, Renaux B, Wijesuriya SJ, and Hollenberg MD (2001) Glycosylation and the activation of proteinase-activated receptor 2 (PAR2) by human mast cell tryptase. *Br J Pharmacol* **134**:705–718.
- Connolly AJ, Ishihara H, Kahn ML, Farese RV Jr, and Coughlin SR (1996) Role of the thrombin receptor in development and evidence for a second receptor. *Nature (Lond)* **381**:516–519.
- Corvera CU, Dery O, McConalogue K, Gamp P, Thoma M, Al-Ani B, Caughey GH, Hollenberg MD, and Bunnett NW (1999) Thrombin and mast cell tryptase regulate guinea-pig myenteric neurons through proteinase-activated receptors-1 and -2. *J Physiol* **517**:741–756.
- Coughlin SR (2000) Thrombin signalling and protease-activated receptors. *Nature (Lond)* **407**:258–264.
- D'Andrea MR, Derian CK, Leturcq D, Baker SM, Brunmark A, Ling P, Darrow AL, Santulli RJ, Brass LF, and Andrade-Gordon P (1998) Characterization of protease-activated receptor-2 immunoreactivity in normal human tissues. *J Histochem Cytochem* **46**:157–164.
- DeFea KA, Zalevsky J, Thoma MS, Dery O, Mullins RD, and Bunnett NW (2000) Beta-arrestin-dependent endocytosis of proteinase-activated receptor 2 is required for intracellular targeting of activated ERK1/2. *J Cell Biol* **148**:1267–1281.
- de Garavilla L, Vergnolle N, Young SH, Ennes H, Steinhoff M, Ossovskaya VS, D'Andrea MR, Mayer EA, Wallace JL, Hollenberg MD, et al. (2001) Agonists of proteinase-activated receptor 1 induce plasma extravasation by a neurogenic mechanism. *Br J Pharmacol* **133**:975–987.
- Dery O, Corvera CU, Steinhoff M, and Bunnett NW (1998) Proteinase-activated receptors: novel mechanisms of signaling by serine proteinases. *Am J Physiol* **274**:C1429–C1452.
- Dery O, Thoma MS, Wong H, Grady EF, and Bunnett NW (1999) Trafficking of proteinase-activated receptor-2 and beta-arrestin-1 tagged with green fluorescent protein. Beta-Arrestin-dependent endocytosis of a proteinase receptor. *J Biol Chem* **274**:18524–18535.
- Even-Ram SC, Maoz M, Pokroy E, Reich R, Katz BZ, Gutwein P, Altevogt P, and Bar-Shavit R (2001) Tumor cell invasion is promoted by activation of protease activated receptor-1 in cooperation with the alpha v beta 5 integrin. *J Biol Chem* **276**:10952–10962.
- Even-Ram S, Uziel B, Cohen P, Grisaru-Granovsky S, Maoz M, Ginzburg Y, Reich R, Vlodavsky I, and Bar-Shavit R (1998) Thrombin receptor overexpression in malignant and physiological invasion processes. *Nat Med* **4**:909–914.
- Faruqi TR, Weiss EJ, Shapiro MJ, Huang W, and Coughlin SR (2000) Structure-function analysis of protease-activated receptor 4 tethered ligand peptides. Determinants of specificity and utility in assays of receptor function. *J Biol Chem* **275**:19728–19734.
- Gerszten RE, Chen J, Ishii M, Ishii K, Wang L, Nanevitz T, Turck CW, Vu TK, and Coughlin SR (1994) Specificity of the thrombin receptor for agonist peptide is defined by its extracellular surface. *Nature (Lond)* **368**:648–651.
- Glenn KC, Frost GH, Bergmann JS, and Carney DH (1988) Synthetic peptides bind to high-affinity thrombin receptors and modulate thrombin mitogenesis. *Pept Res* **1**:65–73.
- Griffin CT, Srinivasan Y, Zheng YW, Huang W, and Coughlin SR (2001) A role for thrombin receptor signaling in endothelial cells during embryonic development. *Science (Wash DC)* **293**:1666–1670.
- Hammes SR and Coughlin SR (1999) Protease-activated receptor-1 can mediate responses to SFLLRN in thrombin-desensitized cells: evidence for a novel mechanism preventing or terminating signaling by PAR1's tethered ligand. *Biochemistry* **38**:2486–2493.
- Hammes SR, Shapiro MJ, and Coughlin SR (1999) Shutoff and agonist-triggered internalization of protease-activated receptor 1 can be separated by mutation of putative phosphorylation sites in the cytoplasmic tail. *Biochemistry* **38**:9308–9316.
- Hein L, Ishii K, Coughlin SR, and Kobilka BK (1994) Intracellular targeting and trafficking of thrombin receptors. A novel mechanism for resensitization of a G protein-coupled receptor. *J Biol Chem* **269**:27719–27726.
- Henrikson KP, Salazar SL, Fenton JW 2nd, and Pentecost BT (1999) Role of thrombin receptor in breast cancer invasiveness. *Br J Cancer* **79**:401–406.
- Hollenberg MD (1996) Protease-mediated signalling: new paradigms for cell regulation and drug development. *Trends Pharmacol Sci* **17**:3–6.
- Hollenberg MD, Lanionu AA, Saifeddine M, and Moore GJ (1993) Role of the amino- and carboxyl-terminal domains of thrombin receptor-derived polypeptides in biological activity in vascular endothelium and gastric smooth muscle: evidence for receptor subtypes. *Mol Pharmacol* **43**:921–930.
- Hollenberg MD and Saifeddine M (2001) Proteinase-activated receptor 4 (PAR4): activation and inhibition of rat platelet aggregation by PAR4-derived peptides. *Can J Physiol Pharmacol* **79**:439–442.
- Hollenberg MD, Saifeddine M, and Al-Ani B (1996) Proteinase-activated receptor-2 in rat aorta: structural requirements for agonist activity of receptor-activating peptides. *Mol Pharmacol* **49**:229–233.
- Hollenberg MD, Saifeddine M, Al-Ani B, and Gui Y (1999) Proteinase-activated receptor 4 (PAR4): action of PAR4-activating peptides in vascular and gastric

- tissue and lack of cross-reactivity with PAR1 and PAR2. *Can J Physiol Pharmacol* **77**:458–464.
- Hollenberg MD, Yang SG, Laniyonu AA, Moore GJ, and Saifeddine M (1992) Action of thrombin receptor polypeptide in gastric smooth muscle: identification of a core pentapeptide retaining full thrombin-mimetic intrinsic activity. *Mol Pharmacol* **42**:186–191.
- Hoxie JA, Ahuja M, Belmonte E, Pizarro S, Parton R, and Brass LF (1993) Internalization and recycling of activated thrombin receptors. *J Biol Chem* **268**:13756–13763.
- Hung DT, Wong YH, Vu TK, and Coughlin SR (1992) The cloned platelet thrombin receptor couples to at least two distinct effectors to stimulate phosphoinositide hydrolysis and inhibit adenylate cyclase. *J Biol Chem* **267**:20831–20834.
- Ishihara H, Connolly AJ, Zeng D, Kahn ML, Zheng YW, Timmons C, Tram T, and Coughlin SR (1997) Protease-activated receptor 3 is a second thrombin receptor in humans. *Nature (Lond)* **386**:502–506.
- Ishii K, Chen J, Ishii M, Koch WJ, Freedman NJ, Lefkowitz RJ, and Coughlin SR (1994) Inhibition of thrombin receptor signaling by a G-protein coupled receptor kinase. Functional specificity among G-protein coupled receptor kinases. *J Biol Chem* **269**:1125–1130.
- Kahn ML, Nakanishi-Matsui M, Shapiro MJ, Ishihara H, and Coughlin SR (1999) Protease-activated receptors 1 and 4 mediate activation of human platelets by thrombin. *J Clin Invest* **103**:879–887.
- Kahn ML, Zheng YW, Huang W, Bigornia V, Zeng D, Moff S, Farese RV Jr, Tam C, and Coughlin SR (1998) A dual thrombin receptor system for platelet activation. *Nature (Lond)* **394**:690–694.
- Kamath L, Meydani A, Foss F, and Kuliopulos A (2001) Signaling from protease-activated receptor-1 inhibits migration and invasion of breast cancer cells. *Cancer Res* **61**:5933–5940.
- Kawabata A, Saifeddine M, Al-Ani B, Leblond L, and Hollenberg MD (1999) Evaluation of proteinase-activated receptor-1 (PAR1) agonists and antagonists using a cultured cell receptor desensitization assay: activation of PAR2 by PAR1-targeted ligands. *J Pharmacol Exp Ther* **288**:358–370.
- Kimura M, Andersen TT, Fenton JW 2nd, Bahou WF, and Aviv A (1996) Plasmin-platelet interaction involves cleavage of functional thrombin receptor. *Am J Physiol* **271**:C54–C60.
- Kinlough-Rathbone RL, Rand ML, and Packham MA (1993) Rabbit and rat platelets do not respond to thrombin receptor peptides that activate human platelets. *Blood* **82**:103–106.
- Kong W, McConalogue K, Khitin LM, Hollenberg MD, Payan DG, Bohm SK, and Bunnett NW (1997) Luminal trypsin may regulate enterocytes through proteinase-activated receptor. *Proc Natl Acad Sci USA* **94**:8884–8889.
- Koshikawa N, Nagashima Y, Miyagi Y, Mizushima H, Yanoma S, Yasumitsu H, and Miyazaki K (1997) Expression of trypsin in vascular endothelial cells. *FEBS Lett* **409**:442–448.
- Krupnick JG and Benovic JL (1998) The role of receptor kinases and arrestins in G protein-coupled receptor regulation. *Annu Rev Pharmacol Toxicol* **38**:289–319.
- Kuliopulos A, Covic L, Seeley SK, Sheridan PJ, Helin J, and Costello CE (1999) Plasmin desensitization of the PAR1 thrombin receptor: kinetics, sites of truncation and implications for thrombolytic therapy. *Biochemistry* **38**:4572–4585.
- Lafleur MA, Hollenberg MD, Atkinson SJ, Knauper V, Murphy G, and Edwards DR (2001) Activation of pro-(matrix metalloproteinase-2) (pro-MMP-2) by thrombin is membrane-type-MMP-dependent in human umbilical vein endothelial cells and generates a distinct 63 kDa active species. *Biochem J* **357**:107–115.
- Lerner DJ, Chen M, Tram T, and Coughlin SR (1996) Agonist recognition by proteinase-activated receptor 2 and thrombin receptor. Importance of extracellular loop interactions for receptor function. *J Biol Chem* **271**:13943–13947.
- Loew D, Perrault C, Morales M, Moog S, Ravanat C, Schuhler S, Arcone R, Pietropalo C, Cazenave JP, van Dorsselaer A, and Lanza F (2000) Proteolysis of the exodomain of recombinant protease-activated receptors: prediction of receptor activation or inactivation by mass spectrometry. *Biochemistry* **39**:10812–10822.
- Ma L, Hollenberg MD, and Wallace JL (2001) Thrombin-induced platelet endostatin release is blocked by a proteinase activated receptor-4 (PAR4) antagonist. *Br J Pharmacol* **134**:701–704.
- Macfarlane SR, Scatter MJ, Kanke T, Hunter GD, and Plevin R (2001) Proteinase-activated receptors. *Pharmacol Rev* **53**:245–282.
- Martin CB, Mahon GM, Klingler MB, Kay RJ, Symons M, Der CJ, and Whitehead IP (2001) The thrombin receptor, PAR-1, causes transformation by activation of Rho-mediated signaling pathways. *Oncogene* **20**:1953–1963.
- Maryanoff BE, Santulli RJ, McComsey DF, Hoekstra WJ, Hoey K, Smith CE, Addo M, Darrow AL, and Andrade-Gordon P (2001) Protease-activated receptor-2 (PAR-2): structure-function study of receptor activation by diverse peptides related to tethered-ligand epitopes. *Arch Biochem Biophys* **386**:195–204.
- McRedmond JP, Harriott P, Walker B, and Fitzgerald DJ (2000) Streptokinase-induced platelet activation involves antistreptokinase antibodies and cleavage of protease-activated receptor-1. *Blood* **95**:1301–1308.
- Molino M, Barnathan ES, Numerof R, Clark J, Dreyer M, Cumashi A, Hoxie JA, Schechter N, Woolkalis M, and Brass LF (1997) Interactions of mast cell tryptase with thrombin receptors and PAR-2. *J Biol Chem* **272**:4043–4049.
- Molino M, Blanchard N, Belmonte E, Tarver AP, Abrams C, Hoxie JA, Cerletti C, and Brass LF (1995) Proteolysis of the human platelet and endothelial cell thrombin receptor by neutrophil-derived cathepsin G. *J Biol Chem* **270**:11168–11175.
- Nakanishi-Matsui M, Zheng YW, Sulciner DJ, Weiss EJ, Ludeman MJ, and Coughlin SR (2000) PAR3 is a cofactor for PAR4 activation by thrombin. *Nature (Lond)* **404**:609–613.
- Nanevitz T, Ishii M, Wang L, Chen M, Chen J, Turck CW, Cohen FE, and Coughlin SR (1995) Mechanisms of thrombin receptor agonist specificity. Chimeric receptors and complementary mutations identify an agonist recognition site. *J Biol Chem* **270**:21619–21625.
- Natarajan S, Rixinger D, Peluso M, and Seiler SM (1995) 'Tethered ligand' derived pentapeptide agonists of thrombin receptor: a study of side chain requirements for human platelet activation and GTPase stimulation. *Int J Pept Protein Res* **45**:145–151.
- Nystedt S, Emilsson K, Wahlestedt C, and Sundelin J (1994) Molecular cloning of a potential proteinase activated receptor. *Proc Natl Acad Sci USA* **91**:9208–9212.
- Oberst M, Anders J, Xie B, Singh B, Ossandon M, Johnson M, Dickson RB, and Lin CY (2001) Matriptase and HAI-1 are expressed by normal and malignant epithelial cells in vitro and in vivo. *Am J Pathol* **158**:1301–1311.
- O'Brien PJ, Molino M, Kahn M, and Brass LF (2001) Protease activated receptors: theme and variations. *Oncogene* **20**:1570–1581.
- O'Brien PJ, Prevost N, Molino M, Hollinger MK, Woolkalis M, Woulfe DS, and Brass LF (2000) Thrombin responses in human endothelial cells. Contributions from receptors other than PAR1 include the transactivation of PAR2 by thrombin-cleaved PAR1. *J Biol Chem* **275**:13502–13509.
- Offermanns S, Laugwitz KL, Spicher K, and Schultz G (1994) G proteins of the G12 family are activated via thromboxane A2 and thrombin receptors in human platelets. *Proc Natl Acad Sci USA* **91**:504–508.
- Pakala R, Liang CT, and Benedict CR (2000) Inhibition of arterial thrombosis by a peptide ligand of the thrombin receptor. *Thromb Res* **100**:89–96.
- Rasmussen UB, Gachet C, Schlesinger Y, Hanau D, Ohlmann P, Van Obberghen-Schilling E, Pouyssegur J, Cazenave JP, and Pavirani A (1993) A peptide ligand of the human thrombin receptor antagonizes alpha-thrombin and partially activates platelets. *J Biol Chem* **268**:14322–14328.
- Rasmussen UB, Vouret-Craviari V, Jallat S, Schlesinger Y, Pages G, Pavirani A, Lecocq JP, Pouyssegur J, and VanObberghen-Schilling E (1991) cDNA cloning and expression of a hamster alpha-thrombin receptor coupled to Ca²⁺ mobilization. *FEBS Lett* **288**:123–128.
- Rotella D (2001) Protease-activated receptor antagonists. *Report of the 221st American Chemical Society National Meeting* (part XV); 2001 April 1–5; San Diego, CA. *Curr Opin Drug Discov Devel* **4**:625–626.
- Roy SS, Saifeddine M, Loutzenhiser R, Triggle CR, and Hollenberg MD (1998) Dual endothelium-dependent vascular activities of proteinase-activated receptor-2-activating peptides: evidence for receptor heterogeneity. *Br J Pharmacol* **123**:1434–1440.
- Sambrano GR, Huang W, Faruqi T, Mahrus S, Craik C, and Coughlin SR (2000) Cathepsin G activates protease-activated receptor-4 in human platelets. *J Biol Chem* **275**:6819–6823.
- Sambrano GR, Weiss EJ, Zheng YW, Huang W, and Coughlin SR (2001) Role of thrombin signalling in platelets in haemostasis and thrombosis. *Nature (Lond)* **413**:74–78.
- Scarborough RM, Naughton MA, Teng W, Hung DT, Rose J, Vu TK, Wheaton VI, Turck CW, and Coughlin SR (1992) Tethered ligand agonist peptides. Structural requirements for thrombin receptor activation reveal mechanism of proteolytic unmasking of agonist function. *J Biol Chem* **267**:13146–13149.
- Seiler SM, Peluso M, Michel IM, Goldenberg H, Fenton JW 2nd, Rixinger D, and Natarajan S (1995) Inhibition of thrombin and SFLLR-peptide stimulation of platelet aggregation, phospholipase A2 and Na⁺/H⁺ exchange by a thrombin receptor antagonist. *Biochem Pharmacol* **49**:519–528.
- Shapiro MJ, Trejo J, Zeng D, and Coughlin SR (1996) Role of the thrombin receptor's cytoplasmic tail in intracellular trafficking. Distinct determinants for agonist-triggered versus tonic internalization and intracellular localization. *J Biol Chem* **271**:32874–32880.
- Shapiro MJ, Weiss EJ, Faruqi TR, and Coughlin SR (2000) Protease-activated receptors 1 and 4 are shut off with distinct kinetics after activation by thrombin. *J Biol Chem* **275**:25216–25221.
- Soslau G, Class R, Morgan DA, Foster C, Lord ST, Marchese P, and Ruggeri ZM (2001) Unique pathway of thrombin-induced platelet aggregation mediated by glycoprotein Ib. *J Biol Chem* **276**:21173–21183.
- Steinhoff M, Vergnolle N, Young SH, Tognetto M, Amadesi S, Ennes HS, Trevisani M, Hollenberg MD, Wallace JL, Caughey GH, et al. (2000) Agonists of proteinase-activated receptor 2 induce inflammation by a neurogenic mechanism. *Nat Med* **6**:151–158.
- Suidan HS, Bouvier J, Schaerer E, Stone SR, Monard D, and Tschopp J (1994) Granzyme A released upon stimulation of cytotoxic T lymphocytes activates the thrombin receptor on neuronal cells and astrocytes. *Proc Natl Acad Sci USA* **91**:8112–8116.
- Sun G, Stacey MA, Schmidt M, Mori L, and Mattoli S (2001) Interaction of mite allergens der p3 and der p9 with protease-activated receptor-2 expressed by lung epithelial cells. *J Immunol* **167**:1014–1021.
- Swift S, Sheridan PJ, Covic L, and Kuliopulos A (2000) PAR1 thrombin receptor-G protein interactions. Separation of binding and coupling determinants in the galpha subunit. *J Biol Chem* **275**:2627–2635.
- Takeuchi T, Harris JL, Huang W, Yan KW, Coughlin SR, and Craik CS (2000) Cellular localization of membrane-type serine protease 1 and identification of protease-activated receptor-2 and single-chain urokinase-type plasminogen activator as substrates. *J Biol Chem* **275**:26333–26342.
- Trejo J and Coughlin SR (1999) The cytoplasmic tails of protease-activated receptor-1 and substance P receptor specify sorting to lysosomes versus recycling. *J Biol Chem* **274**:2216–2224.
- Vassallo RR Jr, Kieber-Emmons T, Cichowski K, and Brass LF (1992) Structure-function relationships in the activation of platelet thrombin receptors by receptor-derived peptides. *J Biol Chem* **267**:6081–6085.
- Vergnolle N, Bunnett NW, Sharkey KA, Brussee V, Compton SJ, Grady EF, Cirino G, Gerard N, Basbaum AI, Andrade-Gordon P, et al. (2001a) Proteinase-activated receptor-2 and hyperalgesia: a novel pain pathway. *Nat Med* **7**:821–826.
- Vergnolle N, Macnaughton WK, Al-Ani B, Saifeddine M, Wallace JL, and Hollenberg MD (1998) Proteinase-activated receptor 2 (PAR2)-activating peptides: identification of a receptor distinct from PAR2 that regulates intestinal transport. *Proc Natl Acad Sci USA* **95**:7766–7771.
- Vergnolle N, Wallace JL, Bunnett NW, and Hollenberg MD (2001b) Protease-activated receptors in inflammation, neuronal signaling and pain. *Trends Pharmacol Sci* **22**:146–152.
- Verrall S, Ishii M, Chen M, Wang L, Tram T, and Coughlin SR (1997) The thrombin

- receptor second cytoplasmic loop confers coupling to Gq-like G proteins in chimeric receptors. Additional evidence for a common transmembrane signaling and G protein coupling mechanism in G protein-coupled receptors. *J Biol Chem* **272**:6898–6902.
- Vouret-Craviari V, Grall D, Chambard JC, Rasmussen UB, Pouyssegur J, and Van Obberghen-Schilling E (1995) Post-translational and activation-dependent modifications of the G protein-coupled thrombin receptor. *J Biol Chem* **270**:8367–8372.
- Vu TK, Hung DT, Wheaton VI, and Coughlin SR (1991a) Molecular cloning of a functional thrombin receptor reveals a novel proteolytic mechanism of receptor activation. *Cell* **64**:1057–1068.
- Vu TK, Wheaton VI, Hung DT, Charo I, and Coughlin SR (1991b) Domains specifying thrombin-receptor interaction. *Nature (Lond)* **353**:674–677.
- Xu WF, Andersen H, Whitmore TE, Presnell SR, Yee DP, Ching A, Gilbert T, Davie EW, and Foster DC (1998) Cloning and characterization of human protease-activated receptor 4. *Proc Natl Acad Sci USA* **95**:6642–6646.
- Zhang HC, Derian CK, Andrade-Gordon P, Hoekstra WJ, McComsey DF, White KB, Poulter BL, Addo MF, Cheung WM, Damiano BP, et al. (2001) 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* **44**:1021–1024.