Mechanism of Selective VEGF-A Binding by Neuropilin-1 Reveals a Basis for Specific Ligand Inhibition

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Mechanism of Selective VEGF-A Binding by Neuropilin-1 Reveals a Basis for Specific Ligand Inhibition

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Abstract

Neuropilin (Nrp) receptors function as essential cell surface receptors for the Vascular Endothelial Growth Factor (VEGF) family of proangiogenic cytokines and the semaphorin 3 (Sema3) family of axon guidance molecules. There are two Nrp homologues, Nrp1 and Nrp2, which bind to both overlapping and distinct members of the VEGF and Sema3 family of molecules. Nrp1 specifically binds the VEGF-A164 isoform, which is essential for developmental angiogenesis. We demonstrate that VEGF-A specific binding is governed by Nrp1 residues in the b1 coagulation factor domain surrounding the invariant Nrp C-terminal arginine binding pocket. Further, we show that Sema3F does not display the Nrp-specific binding to the b1 domain seen with VEGF-A. Engineered soluble Nrp receptor fragments that selectively sequester ligands from the active signaling complex are an attractive modality for selectively blocking the angiogenic and chemorepulsive functions of Nrp ligands. Utilizing the information on Nrp ligand binding specificity, we demonstrate Nrp constructs that specifically sequester Sema3 in the presence of VEGF-A. This establishes that unique mechanisms are used by Nrp receptors to mediate specific ligand binding and that these differences can be exploited to engineer soluble Nrp receptors with specificity for Sema3.

Introduction

The Nrp family of receptors coordinate ligand-binding events that mediate endothelial cell migration and proliferation and neuronal chemorepulsion (reviewed in [1]). There are two Nrp homologues, Nrp1 and Nrp2, which share the same overall domain architecture with 44% identity in their primary sequence. Nrp ligands include the VEGF family of pro-angiogenic cytokines [2] and the Sema3 family [3,4] of axon guidance molecules [5]. Both VEGF and Sema3 family of ligands are composed of multiple genes, splice forms, and proteolytic products with different receptor binding specificity and physiological function.

Soluble receptors capable of sequestering specific ligands are an attractive modality for blocking ligand-dependent signaling pathways. VEGF-Trap, a soluble chimera of VEGF receptor (VEGFR), containing the domains necessary for ligand binding [6], has been approved for use as a clinical agent blocking VEGF-A dependent angiogenesis [7]. The identification of endogenously expressed soluble Nrp receptors (sNrp) with anti-tumor activity [8] has prompted interest in the use of engineered Nrp molecules as attractive modality for blocking ligand-dependent signaling pathways. VEGF-Trap, a soluble chimera of VEGF receptor (VEGFR), containing the domains necessary for ligand binding [6], has been approved for use as a clinical agent blocking VEGF-A dependent angiogenesis [7]. The identification of endogenously expressed soluble Nrp receptors (sNrp) with anti-tumor activity [8] has prompted interest in the use of engineered Nrp molecules as an attractive modality for blocking ligand-dependent signaling pathways. VEGF-Trap, a soluble chimera of VEGF receptor (VEGFR), containing the domains necessary for ligand binding [6], has been approved for use as a clinical agent blocking VEGF-A dependent angiogenesis [7].
terminal a1 domain of Nrp1 and Nrp2 selectively binds the soma domain of different Sema3 family members [22–24]. Indeed, a Sema3 binding-deficient Nrp has been reported which disrupts the unique a1/soma interaction [25]. However, since there is no known secondary binding site, the basis for specificity in VEGF binding remains unclear.

It was recently demonstrated that the essential VEGF-A164/165 (VEGF-A) isoform binds preferentially to Nrp1 [16]. The C-terminal arginine binding cleft of the Nrp1-b1 domain is formed by three loops which are a common feature among coagulation factor domains. While the cleft is conserved, a significant number of residues surrounding this binding pocket differ between Nrp1 and Nrp2 and may contribute to the observed ligand binding specificity. Indeed, the L1 loop of the Nrp1-b1 domain has been shown to contribute to the observed preferential binding of VEGF-A to Nrp1 [16]. However, this interaction alone is insufficient to explain the marked difference in potency of VEGF-A binding to Nrp1 and Nrp2, therefore other molecular determinants of this preferential binding must exist. The recently reported Nrp2 mutation, when Nrp2 R287 is replaced with the corresponding Nrp1 E285, shows enhanced VEGF-A binding and, importantly, unchanged binding to Sema3F [9]. Together, these data suggest that the Nrp-b1 domain contains distinct features that govern specific ligand binding and could be exploited to produce specific inhibitors of Nrp ligands. By understanding how selective VEGF binding is achieved, and whether these regions also affect Sema3 binding, a Nrp molecule that specifically binds Sema3 and VEGF-A specificity. A chimeric Nrp1 and Nrp2, and VEGF-A165 were expressed in CHO cells was used to express alkaline phosphatase (AP) fusion proteins from pAPtag-5 (GenHunter, Nashville, TN) [19,27]. AP-Nrp wild-type and mutant proteins from pAPtag-5 (GenHunter, Nashville, TN) [19,27]. AP-Nrp wild-type and mutant proteins were purified. Peptides were resuspended and titrated with AP-VEGF-A (100 μmole p-NPP hydrolyzed/min/L) in incubation buffer (20 mM Tris pH 7.5, 300 mM NaCl) to a final volume of 100μL and incubated with the Nrp1 affinity plates for 1 hr at 25°C. Wells were washed three times with PBS-T using an EL404 plate washer (BioTek, Winooski, VT), and incubated with PBS-T for an additional 5 min. Wash solution was removed, and 100μL of 1x AP Assay Reagent [28] was added. The reaction was quenched by addition of 100μL of 0.5% NaOH. Evolved p-nitrophenol (p-NP) was quantitated at 405 nm using a SpectraMax M5 plate reader (Molecular Devices, Sunnyvale, CA). The IC50 was fit with a non-linear dose-response inhibition curve using Prism (Graphpad Software, La Jolla, CA). The inhibitory potency of Nrp1Chimeric and Nrp2Chimeric was determined using the same method.

AP-Nrp Binding Assay

To assess the role of the Nrp coagulation factor loops in VEGF-A binding, we measured AP-Nrp binding to VEGF-A affinity plates. Affinity plates were prepared by adding 100μL of VEGF-A165 diluted 1/10 in 50 mM Na2CO3 pH 10.4 to a final concentration of 50 ng/μL in 96 well plates. AP-Nrp constructs (724 μmole p-NPP hydrolyzed/min/L) were incubated with VEGF-A affinity plates for 1 hr at 25°C. Plates were washed and retained AP activity quantitated as described above.

AP-Sema3F and AP-Sema3F-Ig-basic Inhibition Assay

Two AP-fusions of Sema3F were prepared, one corresponding to full length Sema3F (AP-Sema3F; residues 20–779) and the other an AP-fusion of the Sema3F Ig and basic domains (AP-Sema3F-Ig-basic; residues 605–779), the domains necessary and sufficient for binding the b1 coagulation factor domain of Nrp [22]. These were used for semaphorin inhibition experiments by Nrp. Nrp1 and Nrp2 were combined with AP-Sema3F (648 μmole p-NPP hydrolyzed/min/L) in incubation buffer and incubated in low density Nrp1 affinity plates for 1 hr at 25°C. Similarly, Nrp1 and Nrp2 were combined with AP-Sema3F-Ig-basic (181 μmole p-NPP hydrolyzed/min/L) in binding buffer and incubated in high density Nrp1 affinity plates for 1 hr at 25°C. High density Nrp1 affinity plates were prepared by adding 100μL of Nrp1 diluted 1/10 in 50 mM Na2CO3 pH 10.4 to a final concentration of 50 ng/μL in 96 well plates. Plates were washed and retained AP activity quantitated as described above.

C-furSema Inhibition Assay

Two peptides corresponding to the C-terminal basic domains of furin processed Sema3A (C-furSema3A; residues 718–769) (NeoPeptide, Cambridge, MA) and Sema3F (C-furSema3F; residues 740–779 [19]) (LifeTein, South Plainfield, NJ) were synthesized, oxidized to form the natural inter-molecular disulfide, and purified. Peptides were resuspended and titrated with AP-VEGF-A (100 μmole p-NPP hydrolyzed/min/L) in incubation buffer and added to low density Nrp1 affinity plates for 1 hr at 25°C. Plates were washed and retained AP activity quantitated as described above.

Materials and Methods

Protein Expression and Purification

The high affinity ligand binding b1b2 domains of human Nrp1 and Nrp2, and VEGF-A165 were expressed in Esherichia coli, as previously reported, and purified according to established procedures [15,19,26]. Chimeric Nrp1 and Nrp2 constructs were generated using the megaprimer method, expressed as a 6XHis-tag fusion from pET28, and purified using immobilized metal affinity chromatography (IMAC) followed by heparin agarose affinity, as with wild-type proteins. Proteins were buffer exchanged into binding buffer (20 mM Tris pH 7.5, 50 mM NaCl).

Large-scale transient transfection of Chinese Hamster Ovary (CHO) cells was used to express alkaline phosphatase (AP) fusion proteins from pAPtag-5 (GenHunter, Nashville, TN) [19,27]. AP-Nrp1 and AP-Nrp2 b1b2 mutants were generated using the megaprimer method. All AP-Nrp wild-type and mutant proteins were produced at similar levels. AP-Nrp conditioned media was concentrated and buffer exchanged into binding buffer. All expression plasmids and mutants were verified by DNA sequencing.

AP-VEGF-A Inhibition Assay

Nrp affinity plates were prepared by adding 100μL of Nrp1 diluted 1/10 in 50 mM Na2CO3 pH 10.4 to a final concentration of 2.5 ng/μL in 96 well high-binding plates (Costar, 9018), incubated for 1 hr at 37°C, washed with PBS-T (PBS, 0.1% Tween20), and stored at 4°C. An AP-fusion of VEGF-A164 (AP-VEGF-A) was utilized for VEGF inhibition experiments [19]. Nrp1 and Nrp2 were combined with AP-VEGF-A (155 μmole p-NPP hydrolyzed/min/L) in incubation buffer (20 mM Tris pH 7.5, 300 mM NaCl) to a final volume of 100μL and incubated with the Nrp1 affinity plates for 1 hr at 25°C. Wells were washed three times with PBS-T using an EL404 plate washer (BioTek, Winooski, VT), and incubated with PBS-T for an additional 5 min. Wash solution was removed, and 100μL of 1x AP Assay Reagent [28] was added. The reaction was quenched by addition of 100μL of 0.5% NaOH. Evolved p-nitrophenol (p-NP) was quantitated at 405 nm using a SpectraMax M5 plate reader (Molecular Devices, Sunnyvale, CA). The IC50 was fit with a non-linear dose-response inhibition curve using Prism (Graphpad Software, La Jolla, CA). The inhibitory potency of Nrp1Chimeric and Nrp2Chimeric was determined using the same method.

Selective Neuropilin Ligand Binding and Inhibition

In the present study we determined the basis for preferential Nrp1 binding to VEGF-A. Mutagenesis of residues surrounding the shared C-terminal arginine binding pocket identifies residues that differ between Nrp1 and Nrp2 and underlie the observed VEGF-A specificity. A chimeric Nrp2, which combines the identified mutations, is capable of binding VEGF-A similarly to Nrp1 whereas a chimeric Nrp1 shows significant loss of VEGF-A binding. We further show that Nrp1 and Nrp2 both bind Sema3F with similar affinity and that both Nrp2 and the chimeric Nrp1 can selectively sequester Sema3. These data establish that unique mechanisms are used by Sema3 and VEGF-A to mediate specific Nrp binding, revealing a basis for the use of engineered Nrp molecules as selective inhibitors of Sema3.
AP-VEGF-A Recovery Assay

To measure the preferential binding of Nrp1 and Nrp2 to Sema3F or VEGF-A the potential of Nrp to promote the recovery of C-furSema [19] mediated inhibition of AP-VEGF-A binding to Nrp1 was assessed. Nrp1 and Nrp2 were combined with both AP-VEGF-A (155 μmole p-NPP hydrolyzed/min/L) and C-furSema3F (45 nM, the concentration at which ~90% inhibition is achieved) in incubation buffer and added to low density Nrp1 affinity plates for 1 hr at 25°C. Plates were washed and retained AP activity quantitated as described above. Retained AP-VEGF-A was reported versus Nrp concentration as the percent of binding observed relative to uninhibited AP-VEGF-A (no C-furSema).

Circular Dichroism

Circular dichroism (CD) spectra were collected using a Jasco J-810 Spectropolarimeter. Wild-type and chimeric proteins were added to a 0.1-cm-pathlength cuvette at 10μM in PBS pH 7.4. Spectra were recorded at a speed of 20 nm/min using the average of three accumulations over a range of 205–245 nm. Data are reported as per residue molar ellipticity.

Results

Soluble Nrp1 Selectively Inhibits VEGF-A

To assay the inhibitory potency of Nrp1 and Nrp2, we tested the ability of Nrp1 and Nrp2 to inhibit VEGF-A binding to Nrp1 affinity plates in a dose dependent manner (Figure 1). Nrp1 was able to potently inhibit the binding of VEGF-A to Nrp1 affinity plates with an IC50 = 1.8 μM (log IC50 = −5.7±0.2) (black line, Figure 1). In contrast, Nrp2 was able to inhibit binding only at the highest concentrations with an IC50 > 310 μM (log IC50 = −3.5±0.4) (grey line, Figure 1). Each experiment was performed in triplicate with unique protein preparations to provide a direct measurement of inter-assay variability, with 11% inter-assay variability observed for Nrp1 compared to 3.5% intra-assay variability (Figure S1). These data demonstrate, both qualitatively and quantitatively, the robust quality and reproducibility of the reported data. The greater than 100-fold difference in IC50 between Nrp1 and Nrp2 is consistent with the previously reported VEGF binding selectivity [16].

Identification of the Regions of Nrp1 that Confer Selective VEGF-A Binding

The selective ability of Nrp1 to inhibit VEGF-A binding led us to consider the mechanism of this specificity. The predominant Nrp structural determinants mediating VEGF-A binding have been localized to domain b1 [9,16,25]. The b1 domains of Nrp1 and Nrp2 are 52% identical. Conserved between both are the residues which form the C-terminal arginine binding pocket demonstrated to be essential for VEGF-A/Nrp binding [15] (Figure 2A, asterisk). Alignment of Nrp1 and Nrp2 b1 domains reveals diversity in the primary sequence of residues surrounding the binding pocket. There are three different categories of residues: those that are well conserved in both Nrp1 and Nrp2, those that are not well conserved, and those which are distinct between Nrp1 and Nrp2 but well conserved within each ortholog. We hypothesized that residues in this last category likely underlie the observed specific Nrp1/VEGF-A binding.

Further, residues nearby the binding pocket, especially those in the coagulation-factor loops (L1–L3) often utilized in ligand binding in coagulation-factor domain proteins [29], most likely underlie specific binding.

Based on these two criteria, i.e., that residues are separately conserved within Nrp1 and Nrp2 and that they are nearby the binding site, four regions were selected: Nrp1:285/Nrp2:287, Nrp1:299-TN-300/Nrp2:301-DGR-303, Nrp1:304-ER-305/Nrp2:307-QQ-308, and Nrp1:350-KKK-352/Nrp2:353-QNG-355 (Figure 2B). Mutant proteins were produced by swapping the selected sequences between the two Nrp homologues. Nrp residues that contribute to the observed specificity would be expected to reduce Nrp1 binding and enhance Nrp2 binding when reversed. These chimeric Nrp molecules were expressed with an N-terminal AP tag. The binding of AP-Nrp constructs to VEGF-A affinity plates was measured and normalized relative to wild-type Nrp1 or Nrp2 binding. Reduced binding to VEGF-A was observed for all Nrp1 chimeras relative to wild-type Nrp1 (Figure 2C), suggesting a role of these sequences in VEGF-A binding. Three of the four Nrp2 chimeras showed enhanced affinity for VEGF-A relative to wild-type Nrp2 (Figure 2D). The reduction in VEGF-A binding for both Nrp1 ER/QQ and Nrp2 QQ/ER suggests that these mutations may destabilize the protein and this mutation was therefore excluded from further study. These results suggest that E285, 299-TN-300 and 350-KKK-352 of the Nrp1-b1 domain contribute to selective VEGF-A binding.

Nrp2 Chimera Inhibits VEGF-A Binding

To assess whether the identified loops compose the predominant features of the Nrp1-b1 domain that confer specific VEGF-A binding, we generated a Nrp1 and Nrp2 molecule which incorporated all three different mutations in a single construct, termed Nrp1 Chimera and Nrp2 Chimera. To ensure that the mutant proteins were well folded, CD was utilized to assess wild-type and chimeric constructs (Figure 3A). All proteins produce spectra consistent with the expected β-sandwich architecture of the protein. Further, wild-type and mutant proteins show superimposable spectra demonstrating that the mutations are not structurally deleterious. As a quantitative measure of the selectivity of
Nrp1 and Nrp2 play diverse roles in multiple signaling pathways. They are involved in various biological processes such as vascular remodelling, neuron migration, and angiogenesis.

The Nrp1 and Nrp2 receptors are members of the semaphorin family and bind to VEGF-A and semaphorin ligands, respectively. The b1b2 domains of Nrp1 and Nrp2 mediate specific ligand binding via a dual-site binding mechanism. The Sema3 family of ligands includes Sema3F and Sema3A, which bind to Nrp receptors via a dual-site binding mechanism. The Sema3 family of ligands has been demonstrated to utilize their basic C-terminus for equivalent high-affinity binding to the Nrp b1b2 domains, and that this binding is competitive with VEGF-A binding.

IC50 values were used to quantify the potency of Nrp2 in inhibiting VEGF-A binding. Nrp2 exhibited a significant loss in potency with an IC50 = 1.2 nM (log IC50 = 6.2) compared to wild-type Nrp1, IC50 = 0.3 nM (log IC50 = 5.6). Nrp2 has markedly reduced binding to VEGF-A compared to wild-type.

Inhibition of AP-VEGF-A Binding to Nrp1

AP-Nrp2 and Nrp1Chimera proteins for VEGF-A, we assayed the potency of Nrp1Chimera and Nrp2Chimera in inhibiting AP-VEGF-A binding to Nrp1 affinity plates (Figure 3B). The dose-dependent ability of these constructs to inhibit VEGF-A binding was compared to wild-type Nrp1 and Nrp2 (Figure 1). The Nrp1Chimera showed a significant loss in potency, with an IC50 = 62 μM (log IC50 = −4.2±0.2) (blue line, Figure 3B), compared to wild-type Nrp1 (black line, Figure 1). Strikingly, Nrp2Chimera gained over 70-fold potency relative to Nrp2, with an IC50 = 3.9 μM (log IC50 = −5.4±0.2) (green line, Figure 3B), nearly to the level observed for wild-type Nrp1.

Nrp1 and Nrp2 Equivalently Inhibit Sema3F Binding

VEGF and semaphorin are the two major ligand families of Nrp receptors. The Sema3 family of ligands has been demonstrated to bind Nrp receptors via a dual-site binding mechanism. The Sema3 semaphorin domain mediates specific ligand binding via the Nrp a1 domain [23] and the Sema3 basic C-terminal mediates common high-affinity binding to the Nrp b1b2 domains [25]. To confirm that the Nrp1 and Nrp2 b1b2 domains bind to Sema3, and that they do not display specificity, we measured their ability to inhibit the binding of AP-Sema3F to Nrp1. Both Nrp1 and Nrp2 showed a dose-dependent inhibition of AP-Sema3F binding with equivalent observed potency for Nrp1, IC50 = 2.0 μM (log IC50 = −5.7±0.1), and Nrp2, IC50 = 2.7 μM (log IC50 = −5.6±0.3) (Figure 4A). To confirm that this interaction is mediated by the C-terminal domains of Sema3, we assayed the ability of Nrp1 and Nrp2 b1b2 domains to inhibit the binding of AP-Sema3F-Ig-bis to Nrp1. Consistent with the potency against full-length Sema3F, Nrp1 inhibited AP-Sema3F-Ig-bis binding with an IC50 = 1.2 μM (log IC50 = −5.9±0.1) and Nrp2 inhibited AP-Sema3F-Ig-basic binding with an IC50 = 6.2 μM (log IC50 = −5.2±0.2) (Figure 4B).

These data demonstrate that the b1b2 domain of Nrp1 and Nrp2 contain structural determinants capable of C-terminal Sema3F binding and that this binding does not show specific binding to the two Nrp homologues. To confirm that the interaction between the basic domain of Sema3F and Nrp1-b1b2 is conserved across the Sema3 family, and that this interaction site overlaps with that for VEGF-A, we measured the binding of a peptide corresponding to the C-terminus of both Sema3F and Sema3A to inhibit VEGF-A binding. C-furSema3F and C-furSema3A, peptides corresponding to the furin-activated forms of Sema3F and Sema3A, respectively, were assayed for their ability to competitively inhibit the binding of VEGF-A. Both peptides showed potent, dose-dependent inhibition of AP-VEGF-A binding with IC50 = 22 nM (log IC50 = −7.7±0.04) and 67 nM (log IC50 = −7.2±0.04) for C-furSema3F and C-furSema3A, respectively. These data confirm that the Sema3 family of ligands utilize their basic C-terminals for equivalent high-affinity binding to the Nrp b1b2 domains, and that this binding is competitive with that of VEGF-A.

Nrp2 and Nrp1Chimera Relieve C-furSema Mediated Inhibition of AP-VEGF-A Binding to Nrp1

Nrp1 and Nrp2 display similar affinity for Sema3F (Figure 4A and 4B) but Nrp2 has markedly reduced binding to VEGF-A relative to Nrp1 (Figure 1). This data suggests that Nrp2 may be a potent and specific inhibitor of Sema3 binding to Nrp receptors. To demonstrate the use of Nrp2 as a selective semaphorin inhibitor, we assayed the ability of Nrp2 to selectively relieve Sema3-dependent inhibition of VEGF-A...
binding. Selectivity would be demonstrated by a reduction of C-furSema mediated-inhibition and resultant gain in AP-VEGF-A binding to Nrp1 affinity plates. Nrp1 showed no ability to relieve the inhibition of Sema3F-mediated inhibition. In fact, Nrp1 directly sequestered VEGF-A at high Nrp concentrations resulting in complete loss of binding as expected (black line, Figure 5). Remarkably, Nrp2 significantly enhanced the amount of VEGF-A retained on Nrp1 plates to 63% the level of retention seen in the absence of inhibition (grey line, Figure 5). This provides direct evidence that Nrp2 is able to directly and specifically sequester Sema3. Similarly, 37% recovery was seen with Nrp1Chimera (blue line, Figure 5), consistent with the reversal of specificity seen for VEGF-A inhibition (Figure 3B). These data demonstrate that the unique mechanisms utilized by Nrp to preferentially bind different members of the Sema3 and VEGF family ligands can be exploited to create Nrp inhibitors specific for different Nrp ligand families.

Figure 3. NrpChimera molecules exhibit reversed VEGF-A specificity. (A) The secondary structure of WT Nrp and NrpChimera was assessed by CD. The overlapping spectra of NrpChimera with wild-type Nrp demonstrate that the incorporated mutations are not structurally deleterious. (B) Nrp1Chimera (blue line) and Nrp2Chimera (green line) were tested for their ability to selectively sequester AP-VEGF-A from Nrp1 adsorbed on affinity plates. The NrpChimera molecules show reversed VEGF-A specificity with Nrp1Chimera having a marked reduction in inhibitory potency (IC₅₀ = 62 µM) and Nrp2Chimera exhibiting a significant gain in potency (IC₅₀ = 3.9 µM). Wild-type Nrp1 (black dotted line, IC₅₀ = 1.8 µM) and Nrp2 (grey dotted line, IC₅₀ = 310 µM) are shown for comparison (data from Figure 1). Experiments were performed in triplicate and reported as the mean ± 1 S.D. doi:10.1371/journal.pone.0049177.g003

Figure 4. Nrp inhibits Sema3F binding through interaction with the C-terminal basic domain. (A) Nrp1 and Nrp2 dependent inhibition of AP-Sema3F binding to Nrp1 affinity plates was measured. Both Nrp homologues showed similar ability to compete for AP-Sema3F binding to Nrp1 affinity plates with Nrp1 inhibiting with an IC₅₀ = 2.0 µM and Nrp2 with an IC₅₀ = 2.7 µM. (B) The ability of Nrp1 and Nrp2 to selectively sequester AP-Sema3F-Ig-basic from Nrp1 adsorbed on affinity plates was assessed. The amount of retained AP-Sema3F-Ig-basic was measured and the Nrp concentration recorded where half-inhibition was achieved. Nrp1 (black line) and Nrp2 (grey line) had similar ability for inhibiting Sema3F binding with IC₅₀ = 1.2 µM and IC₅₀ = 6.2 µM, respectively. (C) Two peptides corresponding to the C-terminal basic domain of Sema3A (C-furSema3A) and Sema3F (C-furSema3F) were analyzed for their ability to inhibit AP-VEGF-A binding to Nrp1 affinity plates. Both peptides potently inhibited binding with an IC₅₀ = 22 nM and 67 nM for C-furSema3F and C-furSema3A, respectively. Experiments were performed in triplicate and reported as the mean ± 1 S.D. doi:10.1371/journal.pone.0049177.g004
Selective Neuropilin Ligand Binding and Inhibition

Discussion

These data establish the basis for selective Nrp ligand binding to the b1 coagulation factor domain of Nrp. While both VEGF and Sema3 ligand families share a partially overlapping ligand binding site in the Nrp b1 domain [19], we demonstrate a series of residues that differ between Nrp1 and Nrp2 and contribute to the observed specific VEGF-A binding.

Nrp2Chimera possesses nearly full reversal of selectivity to the level of Nrp1, indicating that the three altered regions represent the predominant regions mediating specific VEGF-A binding. The TN/DGR L1-loop is highly divergent between Nrp1 and Nrp2 and possesses the only insertion/deletion in the b1 domain. Mutation of this region results in the largest net loss of VEGF-A binding to Nrp1, consistent with a direct interaction involving the b1 coagulation factor domain of Nrp. While both VEGF and Sema3 bind the b1 domain, including E154 discussed above, which contribute to Nrp binding. This suggests that the L3-loop may function by electrostatic steering of VEGF-A. This may represent a general mechanism allowing specific binding of other Nrp1-specific ligands such as VEGF-B and placental growth factor (PIGF) that also possess acidic residues in their heparin-binding domains. In contrast, Sema3 family members and Nrp2-specific VEGF-C and VEGF-D do not possess these acidic residues. A mutant Nrp2 containing R287E has previously been shown to possess enhanced binding to VEGF-A [9]. We show that charge reversal produces a decrease in Nrp1 binding to VEGF-A indicating a direct contribution to ligand binding selectivity. Geretti and colleagues proposed that this may be due to enhancing the electronegative potential of the b1 domain of Nrp2 favoring binding to the electropositive VEGF-A. R287 is located in a helical region directly adjacent to the L1 loop, suggesting that these regions interact to correctly position these two structural elements, and thus the critical ligand binding coagulation factor loops. While the Nrp1Chimera molecules substantially reverse the observed specificity for VEGF-A, the reversal does not quite reach the corresponding wild-type level and one or more additional regions may also contribute to selective binding.

Through understanding the molecular basis for Nrp’s specific binding of its ligands, engineered soluble Nrp receptors can be designed with specificity for a particular ligand. The binding of Sema3F shows little selectivity between Nrp1 and Nrp2. Further, the observed inhibitory potency of Nrp1 for VEGF-A and Sema3F is virtually identical in absolute terms. Thus, Nrp1 was found to be equally capable of sequestering both VEGF-A and Sema3F and suggests that Nrp1 has utility as a broad-spectrum Nrp ligand inhibitor. In contrast, Nrp2 is found to selectively sequester Sema3F. The reported chimeric Nrips have utility for discriminating between the contribution of VEGF-A and Sema3F function in a particular system. Previous work has reported Nrp1 mutations in the a1 domain that allow production of a VEGF-A selective Nrp1 [25]. The Nrp1Chimera reported here represents a complimentary molecule that is selective for Sema3F, with utility in differentiating between specific effects mediated by the different Nrp1 ligands.

The use of soluble Nrp as a modulator of VEGF-mediated angiogenesis has been the target of numerous studies. Soluble Nrp as a modality for blocking the chemorepulsive function of Sema3 is less established even though clear clinical applications exist for neutralizing molecules in spinal cord injury [30]. The efficacy of targeting this signaling axis is demonstrated by a small molecule inhibitor of the Sema3A/Nrp1 interaction [31] that, when given to rats following spinal cord transection, shows enhanced regeneration of axons across the glial scar [32]. Two outstanding issues remain to be solved. First, many members of the Sema3 family can mediate this deleterious axonal repulsion, so a potent pan-Sema3 inhibitory modality is desired. Second, selective inhibition of Sema3 signaling without effecting VEGF-A signaling is desired to maximally promote recovery following injury. Nrp2 molecules engineered for increased potency, by oligomerization with an Fc or related strategy, have the potential to be used as selective Sema3-traps. Additionally, molecules specific for certain members of the Sema3 family could potentially be produced by combinatorial approaches using the a1 domain of Nrp1/Nrp2 for specificity in combination with the b1 domain of Nrp2. Taken together, this study demonstrates the mechanism underlying Nrp coagulation factor domain-mediated ligand binding selectivity and advances the search for potent and selective inhibitors of Nrp signaling.

Supporting Information

Figure S1 Determination of inter-assay variation. The ability of Nrp1 and Nrp2 to inhibit VEGF-A binding to Nrp1 affinity plates was measured in three independent trials to determine inter-assay variation. Nrp1 inhibited with an IC50 = 1.8 μM (orange line), 1.6 μM (red line), and 2.0 μM (magenta line).
The average Nrp1 IC50 deviation of 100 μM with a standard deviation of 0.2 μM. At the concentrations tested, Nrp2 was unable to fully inhibit VEGF-A binding and therefore only an estimate of the Nrp2 IC50 could be made. Nrp2 inhibited with an IC50~310 μM (blue line), =120 μM (green line), and =160 μM (purple line). The average Nrp1 IC50=200 μM with a standard deviation of 100 μM.

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Author Contributions
Conceived and designed the experiments: MWP PX H-FG CWVK. Performed the experiments: MWP PX H-FG. Analyzed the data: MWP CWVK. Wrote the paper: MWP CWVK.

References
1. Zachary IC, Frankel P, Evans IM, Pellet-Manny C (2009) The role of neuropilins in cell signalling. Biochem Soc Trans 37: 1171–1178.
2. Soker S, Takahama S, Miao HQ, Neufeld G, Klagesbrun M (1998) Neuropilin 1 is expressed by endothelial and tumor cells as an isoform-specific receptor for vascular endothelial growth factor. Cell 92: 735–745.
3. He Z, Tessier-Lavigne M (1997) Neuropilin is a receptor for the axonal chemorepellent Semaphorin III. Cell 90: 779–791.
4. Kolodkin AL, Leverood DV, Rose EG, Tai YT, Giger RJ, et al. (1997) Neuropilin is a semaphorin III receptor. Cell 90: 753–762.
5. Nakamura F, Tanaka M, Takahashi T, Kallg RG, Strittmatter SM (1998) Neuropilin-1 extracellular domains mediate semaphorin D/III-induced growth cone collapse. Neuron 21: 1095–1100.
6. Holash J, Davis S, Papadopoulos N, Croll SD, Ho L, et al. (2002) VEGF-Trap: a VEGF blocker with potent antitumor effects. Proc Natl Acad Sci U S A 99: 11395–11399.
7. Stewart MW, Grippon S, Kirkpatrick P (2012) Athlhercept. Nat Rev Drug Discov 11: 269–270.
8. Gagnon ML, Bielenberg DR, Gechman Z, Miao HQ, Takashima S, et al. (2008) Identification of a natural soluble neuropilin-1 that binds vascular endothelial growth factor: In vivo expression and antitumor activity. Proc Natl Acad Sci U S A 104: 6152–6157.
9. Geretti E, Shimizu A, Kurschat P, Klagsbrun M (2007) Site-directed mutagenesis in the B-neuropilin-2 domain selectively enhances its affinity to VEGF165, but not to semaphorin 3F. J Biol Chem 282: 25698–25707.
10. Geretti E, van Meeteren LA, Shimizu A, Dudley AC, Clashen-Welsch I, et al. (2010) A mutated soluble neuropilin-2 B domain antagonizes vascular endothelial growth factor bioactivity and inhibits tumor progression. Mol Cancer Res 8: 1093–1073.
11. de Wit J, Verhaagen J (2003) Role of semaphorins in the adult nervous system. Prog Neurobiol 72: 249–267.
12. Nicou SP, Fransen EH, Eldert EM, Taniguchi M, Verhaagen J (2003) Meningeal cell-derived semaphorin 3A inhibits neurite outgrowth. Mol Cell Neurosci 24: 902–912.
13. De Winter F, Oudega M, Lankhorst AJ, Hamers FP, Blits B, et al. (2002) Injury-induced class 3 semaphorin expression in the rat spinal cord. Exp Neurol 175: 103–114.
14. Fawcett JW (2006) Overcoming inhibition in the damaged spinal cord. J Neurotrauma 23: 371–383.
15. Vander Kooi CW, Jasino MA, Pernan B, Neau DB, Bellamy HD, et al. (2007) Structural basis for ligand and heparin binding to neuropilin B domains. Proc Natl Acad Sci U S A 104: 6152–6157.
16. Parker MW, Xu P, Li X, Vander Kooi CW (2012) Structural basis for the selective vascular endothelial growth factor-A (VEGF-A) binding to neuropilin-1. J Biol Chem.
17. Sciarra A, Ladisa P, Vaasay R, Badache S, Bouchenal N, et al. (2007) Structure-function analysis of the antiangiogenic ATWLPPR peptide inhibiting VEGF165 binding to neuropilin-1 and molecular dynamics simulations of the ATWLPPR/neuropilin-1 complex. Peptides 28: 2397–2402.
18. Adams RH, Lehrman M, Kilbrannan A, Betz H, Poschel AW (1997) The chemorepulsive activity of secreted semaphorin is regulated by furin-dependent proteolytic processing. EMBO J 16: 6077–6086.
19. Parker MW, Hellman LM, Xu P, Fried MG, Vander Kooi CW (2010) Furin processing of semaphorin 3F determines its anti-angiogenic activity by regulating direct binding and competition for neuropilin. Biochemistry 49: 4068–4075.
20. Kallkaitinen MJ, Saaristo A, Jussila I, Karlja KA, Lawrence EC, et al. (2001) A model for gene therapy of human hereditary lymphedema. Proc Natl Acad Sci U S A 98: 12677–12682.
21. Giger RJ, Ureghart ER, Gillespie SK, Leverood DV, Ginty DD, et al. (1998) Neuropilin-2 is a receptor for semaphorin IV: insight into the structural basis of receptor function and specificity. Neuron 21: 1079–1092.
22. Chen H, He Z, Bapji A, Tessier-Lavigne M (1998) Semaphorin-neuropilin interactions underlying axonetic axon responses to class III semaphorins. Neuron 21: 1283–1290.
23. Koppel AM, Feiner L, Kobayashi H, Raper JA (1997) A 70 amino acid region within the semaphorin domain activates specific cellular response of semaphorin family members. Neuron 19: 331–347.
24. Merte J, Wang Q, Vander Kooi CW, Sarsfield S, Leahy DJ, et al. (2010) A forward genetic screen in mice identifies Sem3A(K108N), which binds to neuropilin-1 but cannot signal. J Neurosci 30: 5767–5773.
25. Gu C, Limberg BJ, Whitaler GR, Perum B, Leahy DJ, et al. (2002) Characterization of neuropilin-1 structural features that confer binding to semaphorin 3A and vascular endothelial growth factor 165. J Biol Chem 277: 10809–10816.
26. Christinger HW, Muller YA, Berleu LT, Keyt BA, Cunningham BC, et al. (1996) Crystalization of the receptor binding domain of vascular endothelial growth factor. Proteins 26: 353–357.
27. Aricescu AR, La W, Jones EY (2006) A time- and cost-efficient system for high-resolution crystal structures. Curr Protein Pept Sci 3: 313–339.
28. Jardin BA, Zhao Y, Solvaj M, Montes J, Tran R, et al. (2008) Expression of SEAP (secreted alkaline phosphatase) by baculovirus mediated transduction of HEK 293 cells in a hollow fiber bioreactor system. J Biotechnol 135: 272–280.
29. Fuentes-Prior P, Fujikawa K, Pratt KP (2002) New insights into binding interfaces of coagulation factors V and VIII and their homologues lessons from high resolution crystal structures. Curr Protein Pept Sci 3: 313–339.
30. Nicou SP, Eldert EM, Verhaagen J (2006) Chemorepellent axon guidance molecules in spinal cord injury. J Neurotrauma 23: 409–421.
31. Kikuchi K, Kishino A, Konishi O, Kumagai K, Hosotani N, et al. (2003) In vitro and in vivo characterization of a novel semaphorin 3A inhibitor, SM-216289 or xanthoholin. J Biol Chem 278: 42983–42991.
32. Kaneko S, Iwanami A, Nakamura M, Kishino A, Kikuchi K, et al. (2006) A selective Sema3A inhibitor enhances regenerative responses and functional recovery of the injured spinal cord. Nat Med 12: 1300–1309.