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Selectivity of Cell Signaling in the Neuronal Response Based on NGF Mutations and Peptidomimetics in the Treatment of Alzheimers Disease

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1. Introduction

Neurotrophins are maintained at low concentrations by target tissues. They form highly selective interactions with their respective cognate receptors and maintain the viability of neurons in the central and peripheral nervous systems. Overlap in receptor specificities for neurotrophins, in the tissue distribution of the specific receptors, and in the expression of the high affinity receptors enable growth- and survival-enhancing signals to be transduced with great efficiency and specificity over a wide variety of neuronal cells. Early studies suggested that alterations in neurotrophin levels might underlie the pathogenesis of Alzheimer's disease (AD), Parkinson's disease (PD), Huntington's disease (HD) and other neurodegenerative disorders (Apfel et al., 1991; Emilien et al., 2000; Hefti, 1983) [reviewed in (Lad et al., 2003a)]. Today, a strong link between such a neurodegenerative condition and an imbalance in neurotrophin and/or receptor levels has been supported with nerve growth factor (NGF) and AD. A disruption or reduction in critical neurotrophin levels thus leads to widespread neurodegeneration. Conversely, administration of NGF and/or its related family of neurotrophins can potentially play a role in treatment of AD or other degenerative neurological disorders. NGF and its peptidomimetics have been proposed and tested in animal studies and clinical trials for AD with complex responses observed in some patients. Intracellular signaling from the NGF receptors is complex, giving rise to neuronal responses that include differentiation, survival, and apoptosis. This review will focus on novel approaches to eliciting selectivity of a cellular response, based on alterations in the NGF molecule or in the peptidomimetic, that may lead to more effective treatments of AD with NGF-related therapeutics. A conceptual comparison to selectivity in other growth factor receptor systems, such as epidermal growth factor (EGF) and insulin, will also be made.

2. Neurotrophins, their receptors, and neurodegenerative disease

2.1 Neurotrophin receptor interactions

Neurotrophins (NTs) are a family of closely related proteins that have diverse functions ranging from neuronal development, differentiation, and survival to regulation of axonal and dendritic outgrowth, activity-dependent synaptic formation and regulation, cell migration, and cellular proliferation (Diamond et al., 1992; Katz et al., 1990; Levi-Montalcini, 1987; Lindsay, 1988; Segal, 2003). The family of neurotrophins includes nerve growth factor (NGF), brain-derived neurotrophic factor (BDNF), neurotrophin 3 (NT-3), and neurotrophin 4 (NT-4) (Ibanez, 1994; Lad et al., 2003a) . They possess high sequence homology (ca. ~50%) and adopt similar tertiary structures (Fig. 1A) (Bibel & Barde, 2000; Korsching, 1993). The same neurotrophin can affect a variety of neuronal populations and, conversely, the same tissue is capable of receiving stimulatory inputs from multiple neurotrophins. For example, cholinergic basal forebrain (CBF) neurons are attuned to NGF for their maintenance but have been shown to respond to BDNF and NT-3 (Bibel & Barde, 2000; Korsching, 1993; Lad et al., 2003a). The viability of dopaminergic neurons of the substantia nigra has been linked to the actions of BDNF and NT-4 (Hyman et al., 1991; Lad et al., 2003a; Parain et al., 1999). Also, BDNF can act on the entorhinal cortex, the substantia nigra, and the striatum to affect AD, PD, and PD/HD, respectively (Nagahara & Tuszynski, 2011). Each of these neurotrophins binds selectively to a 140-kDa tropomyosin-receptor-kinase, i.e. NGF to TrkA, BDNF and NT-4 to TrkB, and NT-3 to TrkC (Cordon-Cardo et al., 1991; Kaplan et al., 1991; Soppet et al., 1991). Binding to Trk enables the transduction of positive signals, i.e. survival and differentiation through its intracellullar tyrosine kinase domain. In contrast, all neurotrophins can bind a 75-kDa common neurotrophin receptor, p75 (or $p75^{NTR}$), involved in the transduction of negative signals, i.e. growth arrest or apoptosis, when expressed exclusively, or positive signals when co-expressed with Trk receptors (Lad et al., 2003a). The central and peripheral nervous systems possess multiple neurotrophin-dependent cells and tissues that demonstrate co-expression of TrkA and p75.

2.2 Importance of neurotrophins in neurodegenerative disorders

Numerous studies have now demonstrated an imbalance between neurotrophins and their receptors in AD, appearing even in early cognitive defects (Mufson et al., 2007; 2008; Lad, et al., 2003a). In cholinergic basal forebrain (CBF) neurons in AD, TrkA and p75 are decreased at both the mRNA and proteins levels and NGF mRNA is not changed (Mufson et al., 1995; Salehi et al., 2000; S. A. Scott et al., 1995). NGF protein is down in CBF neurons with accumulation of NGF in the cortex, suggesting that retrograde transport to provide the neurotrophic factor to the basal forebrain is impaired (Schindowski et al., 2008). These changes begin to appear in early, pre-clinical stages of cognitive impairment (Ginsberg et al., 2006; Mufson et al., 1995; Mufson et al., 2000; Mufson et al., 2002; Schulte-Herbruggen et al., 2008). In addition, the pro-apoptotic proNGF is elevated, suggesting destruction of neurons containing p75 (Cuello et al., 2010; Fahnestock et al., 2001). A relationship of neurotrophins and their receptors to Aβ toxicity and/or deposition is also becoming apparent (Calissano et al., 2010a; Peng et al., 2004). Finally, BDNF, and possibly its precursor form, is implicated in neuronal survival imbalance in AD (Garzon & Fahnestock, 2007; Peng et al., 2005), particularly in the entorhinal cortex region of the brain (Nagahara & Tuszynski, 2011). Consequently, various treatment strategies have been suggested to slow or reverse cognitive symptoms, utilizing administration of neurotrophins (Mufson et al., 2008; Nagahara & Tuszynski, 2011; Nilsson et al., 2010; Schulte-Herbruggen et al., 2008).

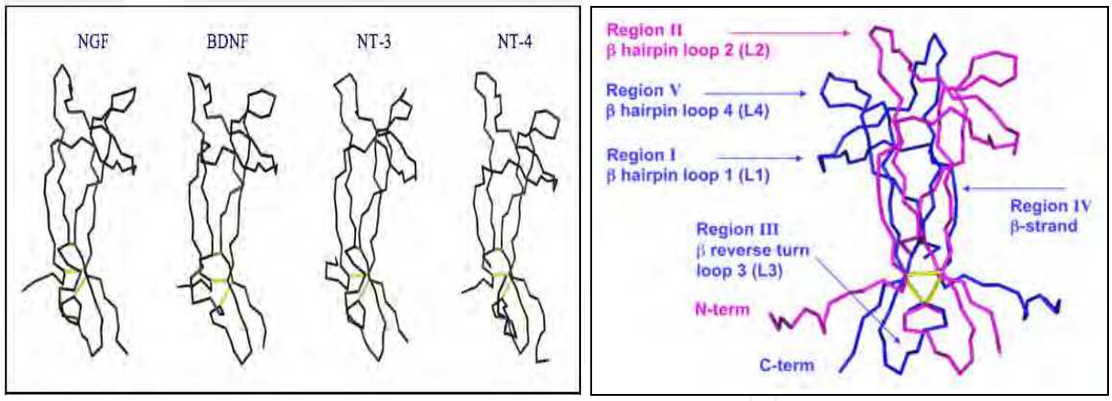

Fig. 1. A (left). Folding of the protomer of the four neurotrophins. B (right). Structure of dimeric NGF showing the loop regions that interact with the receptors. The yellow bonds represent the cystine knot motif. From PDB 1WWW. Note: the variable regions I, II and V defined by sequence homology (Ibanez et al., 1991; Ibanez et al., 1993; Ilag et al., 1994) are equivalent to loops 1, 2, and 4 (L1, L2, L4) defined in the structure (Wiesmann et al., 1999).

2.3 Alzheimer's disease – Treatment strategies

The pathogenesis of Alzheimer's disease is related to loss of NGF-mediated survival signals, receptor imbalances at the cell surface, and a shift to proprotein forms capable of inducing apoptosis. Without these positive signals, the progression of intracellular events that ultimately lead to deposition of tangles and plaques occurs uninterrupted. As a result, neurodegeneration in the cholinergic basal forebrain leads to cognitive and memory deficits demonstrable in AD patients. In the current treatment of Alzheimer's disease, the use of cholinesterase therapies to re-establish critical levels of acetylcholine in the inflicted areas are unable to deter the loss of neuronal populations from the CBF and hence to slow the progression of the disease (Bierer et al., 1995; Lad et al., 2003a). Based on these findings, an appropriate way to reduce or prevent neurodegeneration and maintain viability in Alzheimer's disease is to re-establish NGF signaling within the CBF. Additionally, the administered protein must be well-tolerated and stably released over a long period of time to achieve its trophic effects (Apfel, 2002). However, the direct administration of NGF to the CNS via the circulation is precluded by its inability to cross the blood brain barrier (BBB) (Lad et al., 2003a). Furthermore, subcutaneous delivery of NGF elicits acutely painful phenomena due to the presence of TrkA receptors at free nerve endings of pain fibers (Apfel et al., 1998; Lad et al., 2003a). Finally, gastric secretions would rapidly degrade the protein, making oral preparations ineffective.

Other methods have been considered for delivery of growth factors or protein drugs to the brain [for a broad review see references (Alam et al., 2010; Cattaneo et al., 2008)]. Intranasal inhalation has been demonstrated to be a promising mode of non-invasive, facile delivery of biologics to the brain (Benedict et al., 2011). Monocytes can be loaded to secrete NGF and, in proof of principle, shown to migrate across an *in vitro* BBB model consisting of a brain capillary endothelial cell system (Bottger et al., 2010). Encapsulated cell biodelivery is a modified gene therapy approach which encapsulates cells in a immunoprotective semi-permeable hollow fiber synthetic membrane to secrete the protein factor of interest into the desired region of the brain (Fjord-Larsen et al., 2010); NGF and glial derived neurotrophic

factor (GDNF) are currently undergoing clinical trials with this method in Sweden. Transcranial focused ultrasound (FUS) has been shown to transiently-enhance the permeability of the BBB and permit antibodies, and probably other macromolecules into the intrathecal space (Jordão et al., 2010). Early interest in conjugation of NGF to transferrin or transferrin antibodies as a means of transport across the BBB (Friden et al., 1993; Liao et al., 2001) seems to have waned and shifted toward using this means of cellular uptake for anti-cancer or diabetic drugs.

Gene therapy presents the most-advanced, current means of delivering NGF in a cerebral region-specific manner (Lad et al., 2003a; Nagahara & Tuszynski, 2011). The two main forms of gene therapy that have been used in the delivery of NGF include an *in vivo* approach and an *ex vivo* approach. The former requires the injection of a viral vector containing the gene of interest directly into the region of interest. The latter can be done by transfecting cells with the gene of interest *in vitro* and subsequently transplanting the transfected cells into the region of interest. These techniques overcome the problems initially encountered with NGF delivery by circumventing the BBB, but require surgical manipulation. Additionally, by using viral vectors as the mode of NGF gene delivery into a specific target within the brain, these methods provide a stable, renewable system of NGF synthesis, which can help re-establish receptor levels and counter apoptosis driven by proNGF. However, these forms of therapy provide the greatest benefit during early stages of AD before cholinergic deficits set in.

Initial positive results in rat and primate animal models supported studies of NGF in clinical trials of AD (Bishop et al., 2008; Eriksdotter Jonhagen et al., 1998; Tuszynski et al., 2005). The early clinical trials met with a lack of success due to lack of efficacy, toxicity or both. Common problems in these clinical studies, as well as corresponding animal studies, include undesirable side effects (e.g. hyperinnervation, sprouting, sympathetic stimulation, cachexia, hyperalgesia) (Apfel, 2002; Thoenen & Sendtner, 2002; Winkler et al., 1997) [reviewed in (Nagahara & Tuszynski, 2011)]. Intriguingly, a phase I trial of *ex vivo* NGF gene delivery in mild Alzheimer's disease has shown some promise (Tuszynski et al., 2005). Briefly, eight individuals with early-stage, probable AD were administered primary autologous fibroblasts, which had been genetically modified to synthesize and secrete NGF, via stereotaxic injections to the CBF. This approach was shown to survive grafting into the brain and provided stable NGF secretion for up to 18 months in animal studies with improvement of cholinergic function and memory (Emerich et al., 1994; Tuszynski et al., 2002; Tuszynski et al., 2005). At 22 months of follow up, no adverse side effects were reported in the clinical trial. Mini-Mental State Exam scores demonstrated a reduction in the rate of cognitive decline and 18-fluorodeoxyglucose PET scans demonstrated significantly greater cortical glucose uptake (Tuszynski et al., 2005). Although these observations were encouraging, results must be considered with caution because of the small data set used and the absence of placebo groups. Additionally, NGF demonstrated a large trophic response in the CBF of some of these patients. While this response is necessary for target innervation during development of the nervous system, an adult brain where the axonal infrastructure is well-established might suffer from new and incomplete neuritogenesis in an area receiving dense axonal support. Hence, the generation of a more refined therapeutic molecule is desirable. Since this *ex vivo* trial, the focus of the scientific community has largely shifted to *in vivo* delivery with adeno-associated virus (AAV) (Table 1 and (Nagahara & Tuszynski, 2011; Nilsson et al., 2010).

Interestingly, monoclonal antibodies to NGF were so effective that a Phase III clinical trial for treatment of osteoarthritis of the knee was discontinued because of joint failure due to excessive wear and tear in the absence of the pain sensation (Lane et al., 2010; Wood, 2010).

Disorder	Phase	#	Delivery*	Status	Sponsor
AD	I	8	ex vivo NGF	end 2005 some cognitive improvement (see text)	UCSD
AD	II	50	ICV AAV-NGF Cere-110	Ongoing Recruiting	Ceregene
AD	Ib	6	Encapsulated cell biodelivery NGF	Ongoing	NsGene (Sweden)
HIV associated sensory neuropathy	II	270	SQ NGF	end 2005	NIAID
Osteo-arthritis of knee	III	(a)697 (b)848	IV mAb to NGF	Completed Discontinued (see text)	Pfizer

Table 1. Selected clinical trials of NGF for AD or pain. From clinicaltrials.gov, April 2011.
*Abbreviations: #, number of patients; ICV, intracerebroventricular; AAV, adeno-associated virus; SQ, subcutaneous; IV, intravenous.

3. Signal transduction by neurotrophins

3.1 TrkA signaling

Neurotrophin-mediated signal transduction via the Trk receptors leads to an activation of downstream signaling pathways for survival and differentiation (Bibel & Barde, 2000; Ibanez, 1994; Kaplan & Miller, 2000; Levi-Montalcini, 1987). NGF binding induces TrkA receptor dimerization, transautophosphorylation, and tyrosine kinase ICD activation (Bibel & Barde, 2000; Cunningham & Greene, 1998; Cunningham et al., 1997; Friedman & Greene, 1999). The three major signaling pathways are the phosphotidylinositol-3-kinase (PI3 kinase)/Akt pathway, the Ras/mitogen-activated protein kinase (MAPK) pathway, and the phospholipase C gamma (PLCγ) pathway (Bibel & Barde, 2000; Kaplan & Miller, 2000; Lad et al., 2003a) (See Fig. 2). The PI3 kinase pathway through Akt mediates survival via the suppression of apoptotic proteins and accounts for over 80% of neurotrophin-mediated survival in neurons (Bartlett et al., 1997; Crowder & Freeman, 1998; Kaplan & Miller, 2000). The MAPK pathway, has been implicated in both survival and differentiation, although it has also been implicated in such diverse functions as synaptic plasticity and long-term potentiation (Kaplan & Miller, 2000; Lad et al., 2003a). Depending on the upstream activators and downstream effectors of MAPK, survival, differentiation or both signals can be transduced. For the specific induction of differentiation, a sustained MAPK activation is necessary. The third signal transduction pathway is the PLCγ pathway, involved primarily in Ca2+ regulation of calcium regulated enzymes, neurotrophin secretion, and synaptic

plasticity (Bibel & Barde, 2000; Canossa et al., 1997). These conclusions about distinct pathways have been reached by mutagenesis of the Tyr residues of the Trk-ICD and demonstrate that these signaling pathways can be individually dissected by manipulation of the intracellular initiation of each pathway. TrkB and TrkC have similar signaling pathways but with some individual differences because of the different neuronal environment of these receptors. The division of TrkA signaling into three discrete, but overlapping signal pathways, suggests that pharmaceutical approaches for design of signal selective neurotrophic therapeutics (see Section 5.2) may be able to discriminate among selected paths toward cellular outcomes.

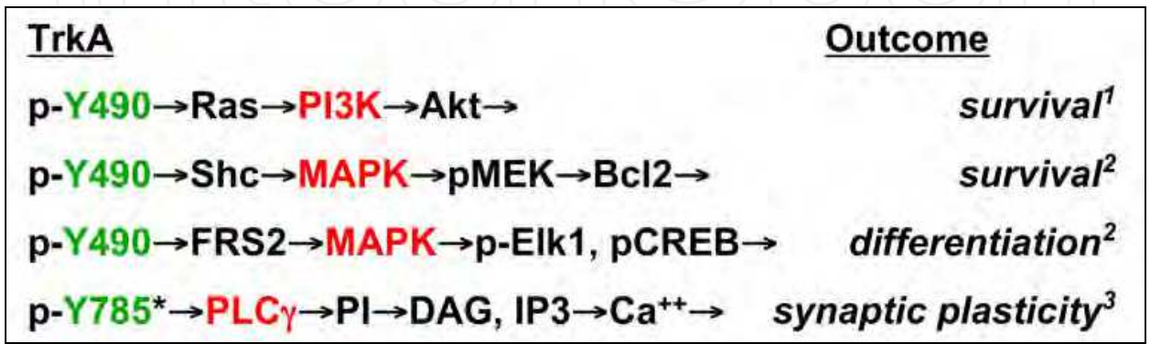

Fig. 2. Signaling pathways, PI3K, MAPK, PLCγ , from TrkA phospho-tyrosines to cell outcomes. *Phosphorylation of Y785 is dependent on phosphorylaton of Y670, Y674, Y675. [1]Bartlett et al., 1997; Crowder & Freeman, 1998; Rodriguez-Viciana et al., 1994; Holgado-Madruga et al., 1997. [2]Kao et al., 2001; Loeb et al., 1994; Gomez & Cohen, 1991; Qian et al., 1998; [3]Loeb et al., 1994; Canossa et al., 1997; Cunningham et al., 1997.

Phosphorylation of a specific set of tyrosines ensues within the activation loop of the kinase domain. These include two tyrosines located in the juxtamembrane domain (Y490) and C-terminus (Y785) of Trk that serve as docking sites for adaptor proteins and three tyrosines (Y670, Y674, and Y675) within the activation loop that interact with nearby basic residues to stabilize a fully functional, active catalytic core and potentiate transduction of downstream signals (Bibel & Barde, 2000; Cunningham & Greene, 1998; Friedman & Greene, 1999; Grewal et al., 1999; Huang & Reichardt, 2003; Kaplan & Miller, 2000; Lad et al., 2003a).

3.2 p75 signaling

Classically, p75 has been thought to be involved in the induction of negative signals like apoptosis and growth arrest in oligodendrocytes, Schwann cells, sympathetic neurons, motor neurons, and sensory neurons (Bamji et al., 1998; Barrett & Bartlett, 1994; Casaccia-Bonnefil et al., 1996; Kaplan & Miller, 2000) in a Trk-independent fashion, (Davey & Davies, 1998; Kaplan & Miller, 2000; Soilu-Hanninen et al., 1999). The co-presence of Trk on a neuron silences pro-apoptotic pathways by activation of the pro-survival transcription factor, NF-κB, which subsequently activates Akt (Bibel & Barde, 2000; Kaplan & Miller, 2000; Khursigara et al., 1999). Sympathetic neurons and basal forebrain neurons that were p75-deficient in p75-/- mice underwent robust axonal sprouting, hypertrophy, or target innervation with naturally-occurring developmental apoptosis being significantly delayed (Kaplan & Miller, 2000; Walsh et al., 1999; Yeo et al., 1997; Bamji et al., 1998). Without intrinsic catalytic activity, the p75 ICD appears to rely on docking of adaptor

proteins. The complexities of the p75 signaling are outlined by representative examples shown in Fig. 3.

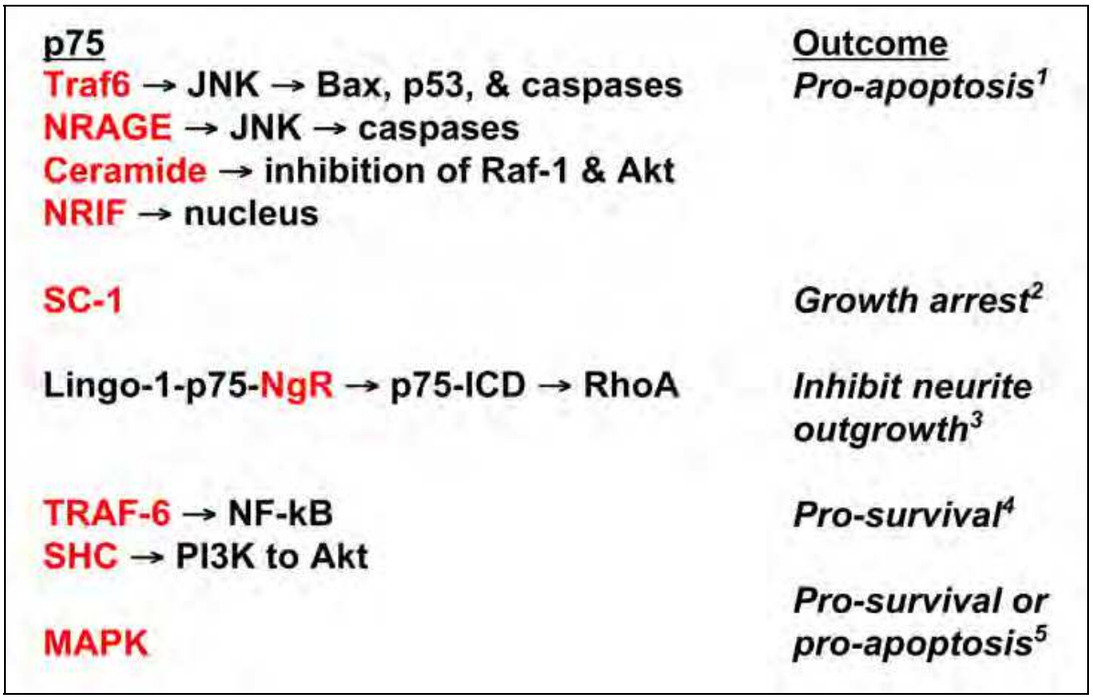

Fig. 3. Some signaling pathways from p75 to cell outcomes. Adaptor proteins interact with p75 to generate most cellular effects of a diverse nature. Uncommon abbrevations: NRAGE, Neurotrophin receptor-interacting MAGE homolog; NRIF, neurotrophin receptor interacting factor, Zn finger transcriptional factor; SC-1, Schwann cell factor 1; NgR, Nogo receptor. RhoA, Ras homolog A. (For reviews see Kaplan & Miller, 2000; Bibel & Barde, 2000; Schecterson & Bothwell, 2010). [1]Aloyz et al., 1998; Salehi, et al., 2002; Muller, et al., 1998; de Chaves et al., 1997; Casademunt, et al., 1999; [2]Chittka & Chao, 1999; [3]Domeniconi et al., 2005; [4]Khursigara et al., 1999; [5]Susen, et al., 1999; Lad & Neet, 2003.

The self-interaction of p75 also influences cellular outcome. Biophysical and biochemical methods have suggested that homomeric p75 plays a pro-apoptotic role while formation of oligomers abolishes this effect and may even serve an anti-apoptotic role (Kaplan & Miller, 2000; Lad et al., 2003a; Wang et al., 2000). Recently, evidence has been provided to support a model in which the formation of an inter-protomer disulfide bond in p75 allows a scissoring (or snail-tong) action upon NGF binding that promotes binding of intracellular adaptor proteins (Simi & Ibanez, 2010; Vilar et al., 2009).

As mentioned above (Section 2.2), proneurotrophins may play significant role in AD, due to their ability to stimulate p75 in the absence of positive Trk signals thereby promoting apoptosis and death of neurons or glia (Cuello et al., 2010; Fahnestock et al., 2001; Teng, et al. 2010). These effects are thought to be mediated by the same pathways (Fig. 3) as presented for mature NGF (or other neurotrophins). In addition, soluble oligomers of β-amyloid may also interact with p75 to cause apoptotic signals in neuronal tissue of AD or pre-AD patients (Dechant & Barde, 2002; Diarra et al. 2009; Coulson, et al., 2009; Calissano, et al. 2010a; 2010b; Peng, et al., 2004; Susen & Blochl, 2005).

These studies demonstrate that the interaction of neurotrophins or proneurotrophins with p75 can lead to diverse effects that are determined by the developmental state of the organism, the particular cell type within which it is expressed, the additional expression of co-receptors, receptor oligomerization states, and the binding of intracellular adaptors or effectors. The complexity of the p75 pathways suggests that developing signal selective muteins for this receptor would be much more difficult than those outlined for the Trk receptor (Section 5.2) with its more clearly initiated signaling. Since the response of cells is, basically, apoptosis or not, then there would be less advantage at this point in time in generating such reagents for p75.

4. Molecular analysis of neurotrophin structure and rationale of mutations

4.1 Conserved and variable regions defined from sequence and 3-D crystallographic structures

Functional data gathered from systematic mutagenesis studies and through the construction of inter-neurotrophin chimeras coupled with structural data from crystallographic studies have implicated several spatially distinct patches of residues in bestowing receptor specificity to each neurotrophin (Casademunt et al., 1999; de Chaves et al., 1997; Grimes et al., 1997; Ilag et al., 1994; Lad et al., 2003a; Ninkina et al., 1997; Rabizadeh et al., 1993; J. Scott et al., 1983; Walsh et al., 1999; Wiesmann et al., 1999; Yeo et al., 1997) . Sequence alignments of NGF, BDNF, and NT-3 (Ibanez et al., 1992; Ibanez et al., 1991; Ibanez et al., 1993; Ilag et al., 1994; Kullander & Ebendal, 1994; Kullander et al., 1997) demonstrate that each neurotrophin possesses seven variable regions that include the same residue positions. These are the N-terminus (residues 1-9), variable region I (β-hairpin loop 1, residues 23-35), variable region II (β-hairpin loop 2, residues 40-49), variable region III (β-reverse turn loop 3, residues 59-66), variable region IV (β-strand, residues 79-88), variable region V (β-hairpin loop 4, residues 95-99), and the C-terminus (residues 111-118) (Fig. 1B). This homology in clustering translates structurally to variable regions occupying complementary sites on each neurotrophin molecule, which are surface-exposed, enabling these regions to function as sites of receptor contacts (Fig. 4). These regions also define amino acid residues to target for redesign of molecules to alter signaling (see Section 5.2).

4.1.1 The specificity patch

Chimeric molecules retaining the amino terminus, carboxyl terminus, and variable region II of NGF possessed the ability to differentiate sympathetic neurons and activate the TrkA receptor (Ibanez et al., 1991). However, a chimeric molecule that additionally replaced residues 3-9 of the N-terminus reduced TrkA binding, activation, and biological activity to <1% (Ibanez et al., 1993). Other substitution and deletion studies confirmed the importance of the N-terminus in specificity (Kullander et al., 1997; Woo et al., 1995; Kahle et al., 1992; Shih et al., 1994). Data from the crystal structure of human recombinant NGF complexed with the TrkA-d5 domains showed that the amino terminal residues 6-9, which were not well-defined in the original NGF crystal structure, adopted a helical conformation upon complex formation with their side chains almost completely buried in the interface (McDonald et al., 1991; Wiesmann et al., 1999) (Fig. 4). Within the same region, H4, I6, and E11 participated in strong interactions with residues in the ABED TrkA β-sheet. The authors labeled this region the specificity patch suggesting that the most important Trk receptor-

binding determinants lie within the amino terminus (Wiesmann et al., 1999). Residues spanning the specificity patch, i.e. H4, P5, I6, F7, E11, and F12, are clearly important for neurotrophin-Trk interactions and activation.

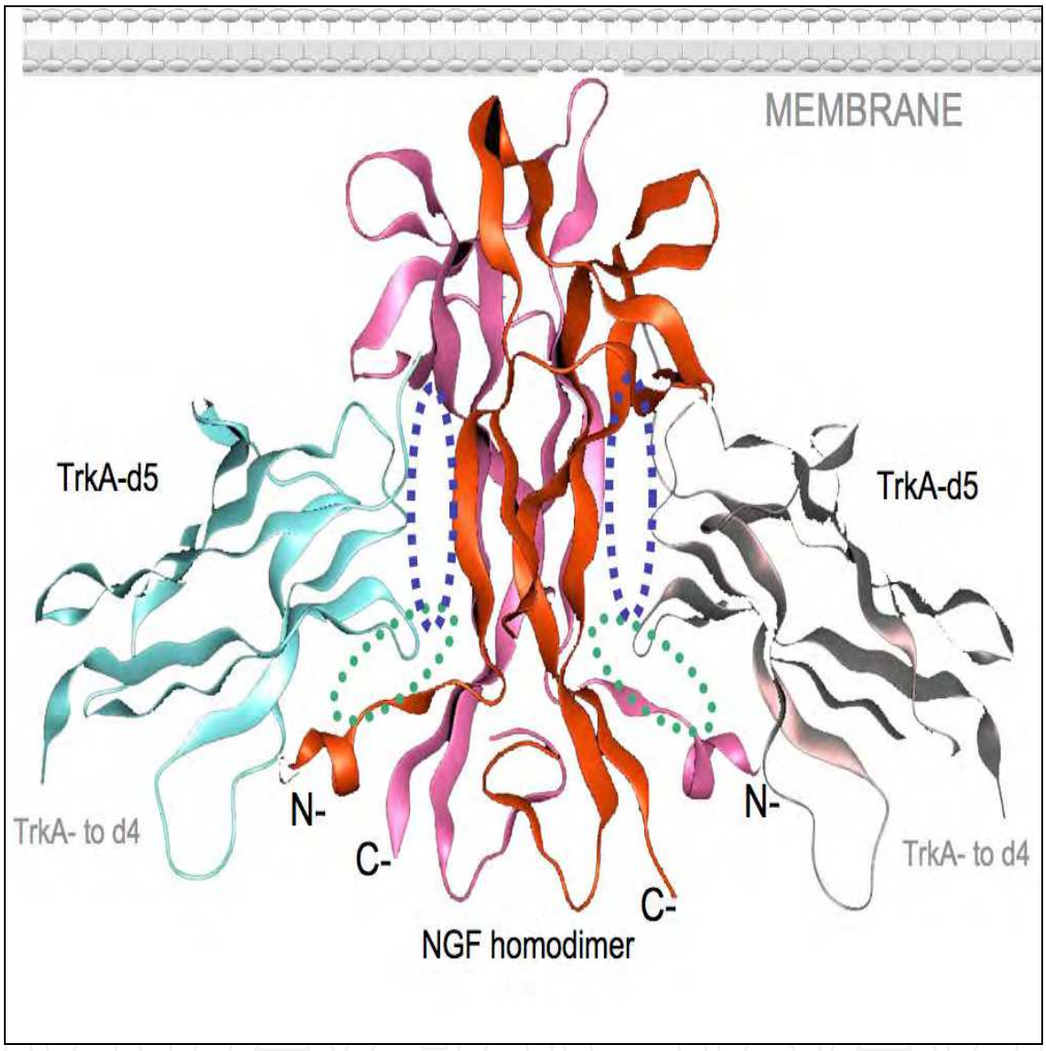

Fig. 4. Schematic representation of dimeric nerve growth factor complexed with two TrkA-d5 domains. NGF and TrkA (PDB 1WWW) form highly specific interactions at the specificity (green dotted oval) and the conserved patch (blue dotted oval). Additional contacts are provided by variable loops I, II, and V (loop 4) that form a continuous surface of binding. Each TrkA-d5 binding site is derived from contributions from loops in both protomers in the NGF dimer. NGF protomers, pink and orange. 1st TrkA-d5; cyan: 2nd TrkA-d5; grey.

4.1.2 The variable regions

The variable regions (Fig. 1B), in general, correspond to loops and surface residues in NGF and the other neurotrophins. Generation of NGF-BDNF chimeras identified variable region II as holding important receptor binding determinants (Ibanez et al., 1991; Ibanez et al., 1993; Ilag et al., 1994; Kullander & Ebendal, 1994; Kullander et al., 1997). The variable region was

further dissected into IIa (residues 40-44) and IIb (residues 45-49) (Ibanez et al., 1993). Region IIb was shown to play a more pivotal role than IIa when replacement of only the latter led to a dramatic reduction in receptor activation and biological activity (Ibanez et al., 1993). The variable region II, with help from variable region V (loop 4), was also shown to confer specificity between NT-3 and NGF (Ilag et al., 1994; Kullander & Ebendal, 1994; Kullander et al., 1997). The C-terminal linker region of TrkA could serve as a possible binding partner of this region (Wiesmann et al., 1999) (Fig. 4). Therefore, residues within variable regions IIa and IIb are considered important for neurotrophin activity, i.e. E41, N43, I44, N45, V48, and F49.

4.1.3 The conserved patch

Crystallographic data of dimeric NGF complexed with TrkA-d5 demonstrated that 5 of 10 residues in variable region IV (Y79, T81, T83, H84, and F86) actually form part of the conserved patch that interacts intimately with the TrkA-d5 domains (Wiesmann & de Vos, 2001) (Fig. 4). This 'conserved' patch was so named because 14 of 23 NGF residues are occupied by homologous amino acids in BDNF and NT-3, while 8 of 15 TrkA residues are conserved in TrkB and TrkC (Wiesmann et al., 1999). The conserved patch forms a continuous binding surface for TrkA-d5 and retains high sequence homology across species (Wiesmann et al., 1999) (Fig. 4). Variable region IV, a β-strand, was specifically shown to retain ~90% homology across species. Within this region, T81 and H84 of NGF are replaced by non-homologous amino acids in the other neurotrophins, suggesting that variable region IV does form specific contacts with TrkA (Ibanez et al., 1993) (Fig. 4). Alanine point mutagenesis of H84 and H75 indicated that these residues participated in receptor binding and activation based on a decline in neuritogenesis in PC12 cells and the ability to compete for binding sites with radioactively-labeled wild-type NGF (Woo & Neet, 1996). Similarly, R100 and R103 showed trends akin to H84 with respect to sequence alignment analysis, mutagenesis studies, and crystallographic data. R100 and R103 are not only strictly conserved across species but also within the family of neurotrophins. Crystallographic data suggested that R103 was the most important binding determinant in the conserved patch (Wiesmann et al., 1999) (Fig. 4). [Also see Section 5.1.] Residues V22, I31, F53, and F54 within the conserved patch are also highly conserved across species and between neurotrophin family members. Alanine substitution of these four residues significantly affect TrkA binding by competition assays, intracellular receptor phosphorylation studies, and biological activity in PC12 cells (Ibanez et al., 1990; Ibanez et al., 1992; Ibanez et al., 1993; Guo et al., 1996). Hence, the conserved patch represents a binding epitope wherein residues help form critical interactions between neurotrophins and Trk receptors.

4.1.4 Summary of important regions and residues of the neurotrophin family

Sixteen residues of NGF may be identified as most important for function (Table 2) and can be designated as the specificity patch (H4, P5, I6, F7, E11, and F12), the variable loops (I31, E41, N43, I44, N45, V48, and F49), or the conserved patch (I31, F54, H84, and R103). Additional residues, V22, F53, H75, and R100, may not occupy the conserved patch, *per se*, but are as highly conserved as residues residing within or near the patch. Similar considerations have been made for BDNF and NT-3 (Ibanez et al., 1992; Ibanez et al., 1991; Ibanez et al., 1993; Ilag et al., 1994; Kullander & Ebendal, 1994; Kullander et al., 1997; Suter et al., 1992; Urfer et al., 1997). These regions of the NGF molecule were targeted to obtain the signal selective muteins discussed in Section 5.2.

Specificity Patch – induced N-terminal α-helix; mainly hydrophobic and some H-bond interactions to β-strands ABED of TrkA-d5.	**NGF:** H4, P5, I6, F7, E11, F12 **BDNF:** S4, D5, P6, A7, E11, L12
Conserved Patch – part of hydrophobic core of NGF; interacts with loop EF and C-terminus of TrkA-d5	**NGF:** V22, I31*, F53, F54, H75, H84*, R103 **BDNF:** V22, M31, F53, Y54, H75, Q84, R103
Specificity for NGF vs NT-3: **Loop II-**	**NGF:** E41, N43, I44, N45, V48, F49 **BDNF:** K41, P43, V44, S45 - - **NT-3**: E41, K43, T44, G45, P48, V49
N-terminus-	**NGF:** P5, F7 **NT-3**: H5, S7

Table 2. Important regions of Trk receptor interaction in human NGF and BDNF. Based on crystal structure and mutagenesis analysis of NGF (Mahapatra, 2008; Ibanez et al., 1992; Ibanez et al., 1991; Ibanez et al., 1993; Ilag et al., 1994; Kullander & Ebendal, 1994; Kullander et al., 1997; Wiesmann & de Vos, 2001) and the corresponding regions in BDNF and NT-3. Note: I31 and H84 (with *) also participate in Loop 1 and Loop 4, respectively, as well as the conserved patch.

5. Development of neurotrophin muteins that have potentially improved therapeutic properties

5.1 Receptor selective muteins

Two interesting, complementary, and useful muteins have helped elucidate the role of the two receptors in neurotrophin action. The first discovery was that mutations in the 32-35, loop I area would greatly reduce or eliminate binding to the p75 receptor and leave TrkA binding unimpaired (Ibanez et al 1992; 1993). The triNGF (or KKE) mutein contained the three mutations, K32A/K34A/E35A, and was used to demonstrate the functional interaction between p75 and TrkA in the developing embryo (Ryden, et al., 1997). The mutations in the N-terminus of NGF were shown to be important for TrkA binding in several laboratories (Section 4.1.1). One noteable mutein was the Δ9/13 mutein that bound p75 but not TrkA (Woo et al., 1995), and helped distinguish between differentiation, cell cycle regulation, and apoptosis in PC12 cells (Hughes et al., 2001). Utilization of this Δ9/13 mutein also later indicated a unique role for the 'high affinity' binding complex of p75 and TrkA in PC12 cells (Lad, et al., 2003b). Indeed, the combination of these two receptor muteins, KKE/Δ9/13 has been studied, briefly, and shown to have no observable activity, as expected (Mahapatra, et al., 2009). Both muteins, KKE and Δ9/13, have been used in a rat glaucoma model to interpret the roles of TrkA (neuroprotective) and p75 (neurotoxic) in retinal degeneration (Bai, et al., 2010). KKE, but not wild type NGF, has recently been reported to partially improve learning in a transgenic APP mouse model (overexpression of Swedish and Indiana mutations) with a reduction of soluble cortical β-amyloid levels, but with no improvement in long-term memory (Aboulkassim, et al., 2011). These two receptor selective muteins have potential as an improved therapeutic for disorders in which either TrkA or p75 can be expected, with improved targeting in that case.

In the opposite direction, a neurotrophin mutein has been made that is less restrictive, rather than more restrictive, in binding to Trk receptors. The pan-neurotrophin, PNT, incorporated

elements of variable and conserved regions to produce a mutein that binds to all three receptors, TrkA, TrkB, TrkC (Ibanez, et al., 1993; Ilag, et al., 1995). To the authors' knowledge, a pan-neurotrophin has not been made that was promiscuous for Trk receptors but restricted so as to not bind p75. Such pan-neurotrophins might have utility in the treatment of some neurodegenerative disorders in which multiple receptors indiscriminately needed extra support (Funakoshi, et al., 1998).

The observation of a mutation in NGF that affects the pain response suggests that changes in signaling from mutations in the ligand have already occurred in nature. A nociceptive response is mediated by NGF (Pezet & McMahon, 2006), partly through the TrkA receptor and partly through p75 (Einarsdottir et al., 2004; Indo, 2002; Nicol & Vasko, 2007). In a large family from northern Sweden, an R100W mutation was uncovered within the coding region of NGF. Individuals from this family suffered from insensitivity to both temperature and deep pain perception, while retaining normal mental abilities, a disorder termed hereditary sensory and autonomic neuropathy type V (HSANV) (Einarsdottir et al., 2004). The R100W mutation selectively disrupts binding of NGF to the p75 receptor, while the affinity for TrkA receptor is less affected (Covaceuszach et al., 2010). Also, the consequence of the R100W mutation on p75 receptor binding is greater for mature NGF rather than proNGF. Signaling pathways reflect this selectivity (Capsoni et al., 2011), suggesting that these findings might lead to a 'painless' NGF protein with therapeutic potential. This NGF mutation is an example of a naturally-occurring, receptor-selective change in the neurotrophin.

5.2 Development of signal selective muteins

To alleviate the potentially undesirable effects of inappropriate over extension of neurites during clinical trials (Section 2.3), designer neurotrophins have been developed (Mahapatra et al., 2009). Two survival-specific (or signal-selective, SS) recombinant NGF muteins with decreased differentiation potential were designed from a set of rationally selected mutations within the specificity, conserved, and variable regions of NGF that may play a discriminatory role in signal transduction. One of these muteins is the F7A/H84A/R103A NGF triple mutein, also called SS-1 or 7-84-103 for short. The other signal-selective hextuple mutein is the K32A/K34A/E35A/F7A/H84A/R103A NGF mutein, or called SS-2 or KKE/7-84-103 (Mahapatra et al., 2009). The main difference between the two SS muteins is that the KKE addition to the F7A/H84A/R103A mutation simply makes the hextuple mutein, SS2, incapable of binding p75 (see Section 5.1).

Survival in several cell lines and differentiation in PC12 cells were studied with these recombinant NGF triple and hextuple muteins and compared to wild type NGF. Each of these two muteins induced slightly lower levels of survival in MG139 and PC12 cells with greatly reduced neuritogenesis in PC12 cells. Neuritogenesis data indicated that residues Phe7, His84, and Arg103 played a critical role in biological activity, in agreement with earlier data in the literature (see Section 4). The observed neuritogenic potential of each recombinant triple mutein suggested that His84 (conserved patch) played a discriminatory role in neurite outgrowth. When His84 was mutated to alanine, to make 7-84-103 and KKE/7-84-103, the maximum neuritic response was almost 40% lower than when His84 was left unaltered. With 7-84-103 and KKE/7-84-103, a synergistic effect also occurred when combining mutations to these three residues. These data suggested that mutations within the specificity and conserved patches were more than additive and led to a reduction of neuritogenesis. In 7-84-103 and KKE/7-84-103, the two point mutations were made in close

proximity within the same spatial region, *i.e.* His84 and Arg103, within the conserved patch. Combining mutations in close proximity may have a cumulative effect on ligand-receptor interactions and ultimately reduce the efficiency of some aspects of intracellular signaling. When independent single mutations were incorporated in close proximity within critical regions at the ligand-receptor interface, survival and differentiation were both affected, with a more pronounced effect on neuritogenesis. The greater decrease in differentiation suggests the possibility of multiple binding epitopes for the mediation of survival, while suggesting more limited patches needed for the induction of differentiation. Comparison with binding to immobilized TrkA by surface plasmon resonance suggested that differentiation more closely follows affinity than does survival. Furthermore, similarity in measurements between the recombinant NGF triple mutein and its KKE hextuple counterpart suggested that p75 binding was inconsequential to the induction of survival or differentiation in these cell lines. Studies with ectopically expressed receptors in fibroblast cell lines, MG139 (TrkA+, p75–) and PCNA (TrkA–, p75+), also supported the interpretation that the distinction in signaling properties was due to signaling from the TrkA tyrosine kinase receptor.

The 7-84-103 mutein supported better activation of the PI 3-kinase/Akt survival pathway than the Ras/MAPK pathway, from which differentiation results. These differences in signaling pathways (Akt vs MAPK, see Section 3) indicate that qualitative differences result from a different mode of binding to the receptor, or re-orientation of the receptor upon binding (see Section 6), and are not simply due to an affinity change that affects all signaling pathways equally. In other words, the level of TrkA phosphorylation with 7-84-103 is more efficiently transferred to MAPK and Akt activation for survival than it is for differentiation.

The discrimination ratio, or ratio of relative (to wtNGF) EC50 values, was 30-fold based on the relative EC50 values of 100 and 3.3 for differentiation and survival, respectively (Mahapatra et al., 2009). A 30-fold difference in effective EC50 values, in the pathophysiological context of an early cognitively diseased brain, might be sufficient to greatly reduce unwanted neuritic response while still maintaining neuronal viability. Whether the design of these two signal-selective muteins is optimal at this stage, or whether further improvement in discrimination between survival and differentiation pathways is possible, needs to be examined.

5.3 How can a transmembrane receptor be stimulated from the outside of a cell and initiate different kinds of intracellular signals?

The intricacies of intracellular signaling from tyrosine kinase ICDs are just now being elucidated and are more complicated than might be expected from the simple requirement of a receptor dimer to transautophosphorylate tyrosine residues on its ICD domain. Activation subsequent to ligand binding to the ECD typically requires phosphorylation of a tyrosine in a loop in the active site in order to auto-activate the ICD kinase by moving the loop out of its inhibitory position in the active site (Bae & Schlessinger, 2010; Lemmon & Schlessinger, 2010). Then the kinase continues to phosphorylate tyrosine residues in the C-terminal tail of the adjacent ICD of the receptor tyrosine kinase that provide a docking site for SH2 domain adaptor proteins or enzymes (Bae & Schlessinger, 2010; Jura et al., 2011; Lemmon & Schlessinger, 2010). Three distinct molecular mechanisms have been detected: (i) The activation loop interacts directly with the active site of the kinase and blocks access to

substrates. (ii) The juxtamembrane region interacts with elements within the active site of the kinase to stabilize an inactive conformation. (iii) The C-terminal tail interacts with the active site of the tyrosine kinase domain to stabilize an inactive conformation. In each case, phosphorylation of the appropriate tyrosine relieves the kinase of its inactivation.

Evidence from crystallographic studies of the EGF receptor ICD has suggested an allosteric mechanism of initiating the signaling cascade (X. Zhang et al., 2006). Two distinct EGFR ICD interactions were described: one being a symmetric interaction and the other an asymmetric interaction that is capable of explaining how the EGF signal is transduced across the cell membrane (X. Zhang et al., 2006). Direct contacts occur between the C-lobe of one ICD, acting as an activator, and the N-lobe of another ICD, acting as a receiver. The activator kinase ICD destabilizes autoinhibitory interactions that involve the activation loop of the receiver ICD. Interactions between the docking proteins, Gab1 and Shc, and the EGFR-ICD generate kinetic discrimination between the unliganded and EGF-liganded states (Fan et al., 2004). The formation of the signal transduction 'signalosome' could well depend upon the intricate relationship of the ICDs with docking proteins and, thus, be susceptible to the manner in which the ligand (neurotrophin mutein or peptidomimetic) brought together two Trk ECDs and their connected ICDs with docking partners. In such a scenario, a larger protein ligand, such as EGF or NGF, would seem to be more capable of having multiple ways to force intracellular interactions in the signalosome than a much smaller peptidomimetic with limited 'hot spots' for interaction.

Thus, to explain the NGF mutein data discussed in Section 5.2 (Mahapatra et al., 2009), the wild-type NGF might orient the two ICDs in a signalosome that generates a "normal" ratio of MAPK to Akt activation. In the survival-selective muteins, 7-84-103 and KKE/7-84-103, the orientation of the ICDs or juxtamembrane regions would have been altered such that the output ratio has been shifted in favor of Akt over MAPK signaling and, hence, survival over neuritogenesis.

6. Neurotrophin peptidomimetics and cell signaling

The use of small molecules is often preferable over the use large proteins as pharmacological agents due to their stability, lower manufacturing costs, ability to pass tissue barriers and good pharmacokinetic profiles. The small molecules can be rationally designed to mimic a region of the ligand that is involved in binding to the receptor or involved in activation of the receptor, thus the term 'peptidomimetics'. Binding of a peptidomimetic to the target receptor may not necessarily result in activation and thus these mimetics may act as antagonists or agonists, depending on their ability to induce a functional response. An inability to induce a functional response would mean that a small molecule with good affinity would be a good inhibitor/antagonist. Two terms that are useful in the design of mimetics are pharmacophore and 'hot spots'. The term 'pharmacophore' relates to the steric and electronic interactions of the mimetic that are necessary to bind to the target receptor, either as an agonist or as an antagonist. The term 'hot spot' refers to the regions on the target protein that specifically interact with a ligand to induce a biological response. Hence, the rational design of mimetics utilizes the information from both the pharmacophore and the hot spots to create libraries of compounds that have subtle structural differences, but significant functional differences (Peleshok & Saragovi, 2006).

6.1 Early neurotrophomimetics

Early studies with cyclized monomeric peptides representing the four loop regions (see Fig. 1B) of NGF (LeSauteur et al., 1995) produced antagonists that competed with NGF for binding and inhibited its activity. The most potent antagonist was derived using amino acids from loop 4 (amino acids 92-97); the peptides designed around loop 2 (amino acids 43-48) or loop 1 (amino acids 30-35) were less effective. As expected, potency was also effected by length and amino acid substitution, with linear peptides showing no activity. Formation of the β-turn is not simply defined by the amino acid sequence and the activity requires mimicking of the 3-dimensional conformation (LeSauteur et al., 1995). Interestingly, in cells expressing both TrkA and p75, the addition of an anti-p75 monoclonal antibody (MC192) that synergizes with NGF caused the antagonistic loop 4 mimetics to behave as agonists with phosphorylation of TrkA and induction of neurites (Maliartchouk et al., 2000). Peptides that formed type I or type γL-αR turns showed greater activity in presence of MC192, suggesting that binding between TrkA and the loop 4 region may require an 'induced fit' mechanism (Beglova et al., 2000).

6.2 Small molecule Trk agonists and antagonists

Other studies, however, reported that cyclized monomeric loop 4 peptide mimetics had to be presented as dimers of cyclized peptides to show agonistic activity (Xie et al., 2000). Their dimeric cyclized peptide, involving amino acids 92-96, showed NGF like activity and induced neurite outgrowth and Akt activation in a TrkA- and ERK- dependent manner. Thus, the dimeric peptide was able to induce an NGF-like signal, by binding to and activating TrkA. Modifications in the peptide sequence abolished the agonistic activity, suggesting specificity conferred by the amino acid sequence (Xie et al., 2000). On the other hand, dimerization of a peptidomimetic does not always behave as expected. Conversion of a monovalent peptidomimetic into a divalent mimetic by chemical coupling resulted, surprisingly, in an antagonist (Brahimi et al., 2010).

Loop 1 peptidomimetics show very unique activity. The loop 1 region (amino acids 30-35) has not only been implicated in activation of TrkA, but amino acids K32, K34 and E35 are extremely important for p75 binding (Ibanez et al., 1992; Ibanez et al., 1993) (see Section 5.1). Therefore, this region influences both TrkA and p75 binding. Cyclized monomeric peptidomimetics designed using the β-turn of NT-3 are good TrkC agonists, however some of the peptides showed partial agonistic response towards TrkA. Interestingly, some of the mimetics were able to induce a neurite outgrowth response through TrkA or TrkC, but failed to induce a survival response on TrkA-only expressing cells (Zaccaro et al., 2005). Neurite outgrowth studies were done using PC12 cells which express both TrkA and p75, whereas survival studies were done using TrkA-only expressing 3T3 cells. The authors, therefore, argued that this peptidomimetic binds to a special 'hot spot' on TrkA that is accessible only when p75 is co-expressed. The co-expression of p75 with TrkA could result in formation of the TrkA-p75 heteroreceptor complex and binding of p75 to TrkA, perhaps, results in conformational changes in the receptor, making the 'hot spot' accessible (Zaccaro et al., 2005). The D3 mimetic in this series was also tested in cognitively impaired aged rats and showed rescue of the cholinergic phenotype in the cortex and nucleus basilis (Bruno, et al., 2004) and to improve learning and reduce β–amyloid in APP mice (Aboulkassim, et al., 2011).

6.3 Small molecule p75 agonists and antagonists

In contrast, Longo's group made loop 1 mimetics (LM11A-24 and LM11A-31) that targeted p75 and were able to induce a survival response through p75 in hippocampal neurons (Massa et al., 2006). Hippocampal neurons express TrkB and p75, but not TrkA; therefore, this survival induced by loop 1 mimetics was suggested to result via p75. They further showed that the survival response was lost in hippocampal neurons from p75-/- mice and that these peptides showed competitive binding to p75 but not TrkA, supporting the interpretation that the activity was through p75. The survival response observed was mediated by NF-κB and the PI3K-Akt pathway (Massa et al., 2006). They further demonstrated that the mimetics were able to rescue the neurons from proNGF-induced (Massa et al., 2006) or Aβ-induced (Yang et al., 2008) cell death, which have implications for Alzheimer's pathogenesis. NGF, even though it can bind p75, was not able to prevent the Aβ-induced neuritic dystrophy. Differences between the signaling by the mimetics vs NGF via p75 were also observed. Both NGF and the mimetics were able to inhibit the ability of Aβ to down regulate Akt signaling; in contrast, the peptidomimetics demonstrated p75-dependent inhibition of Aβ-induced GSK3b and Aβ-induced JNK activation, whereas NGF could not affect these latter two activities. Thus, these loop 1 peptidomimetics induced additional survival promoting cell signaling via p75 in presence of Aβ, not observed with NGF via p75 (Yang et al., 2008). Hence, the selectivity progressed from receptor to signaling pathway. From another laboratory, a different loop1-loop4 mimetic was shown to have some ability to reduce neuropathic pain in a rat model (Colangelo, et al., 2008).

6.4 The prognosis for signal selective mimetics

These studies with NGF peptidomimetics illustrate the advances that have been made as well as outlining the complexities involved. Whether a monovalent or a divalent (dimeric) NGF peptidomimetic is functional and most appropriate for clinical use is, as yet, unresolved. Good NGF mimetics at this stage appear to be D3 or its derivatives and LM11A-24 or LM11A-31, although each may potentially be useful for a distinct purpose. Also being developed are TrkB (O'Leary & Hughes, 2003; Fletcher, et al., 2008; Fletcher & Hughes, 2009) and TrkC (Brahimi, et al., 2009; Chen, et al., 2009; Liu, et al., 2010) antagonists/agonists. BDNF mimetics have made progress toward a useful therapeutic reagent with efficacy studies in rodents (Massa et al., 2010). Some of these neurotrophin reagents show receptor selectivity, as well as selective cellular response, i.e. survival vs differentiation (Saragovi et al., 2009). Whether a small peptidomimetic or a modified, full-length NGF protein will ultimately prove to be the most effective clinical reagent for treatment of AD is an open question at present. The pharmacokinetic advantages of a small molecule mimetic may eventually outweigh the limited information content, relative to the full length protein, provided by such a peptide. In other words, will the chemists be able to design sufficient specificity and selectivity into the peptidomimetics to compete with the potential specificity of a 26 kDa neurotrophin protein with its myriad interaction sites? The answer in some cases for selective signaling appears to be yes (Zaccaro et al., 2005; Longo, et al., 2007; Yang et al., 2008). Conversely, will the means of delivery (intracerebroventricular injection, intranasal inhalation, encapsulation) of a full-length neurotrophin mutein be developed sufficiently to make easy administration to the AD brain competitive with a, perhaps, less effective small molecule that is easily delivered? In either case, exquisite signal selectivity to allow ultra-focus may be most effective and/or desirable.

7. Other growth factors with cellular signaling selectivity

Neurotrophins are not the only ligand-receptor system in which molecular engineering approaches have been employed to improve the therapeutic potential. Mutants of both insulin and tumor necrosis factor (TNFα) have also been developed with enhancement of their therapeutic properties. TNFα was re-designed with the intent of improving its death-inducing targeting toward tumors and reducing its systemic side effects (Wajant, et al., 2005; Gerspach, et al., 2009). This attempt is a true challenge with a multifunctional, pleiotropic cytokine such as TNFα; nevertheless some progress has been made. Similarly, insulin has been engineered to improve its stability as a single chain (Hua, et al., 2008), its stability as a zinc 'stapled' hexamer with even longer lasting attributes (Phillips, et al., 2010), and its selectivity for the insulin receptor over the non-cognate IGF-1 receptor (Zhao, et al., 2009). A reported 3-fold improvement in receptor selectivity has the potential of reducing colorectal cancer risk for diabetic patients using insulin replacement therapy (Zhao, et al., 2009). How well these receptor and/or signal selective mutant cytokines/hormones may work in therapeutic trials is still uncertain.

8. Conclusions and the future

The importance of ligand-receptor interactions in AD and other neurodegenerative conditions is well appreciated. Protein levels and mRNA levels for both TrkA and p75 receptors are reduced in early AD even in the presence of stable NGF expression. A shift from mature NGF to proNGF, which binds p75 and induces apoptosis, has also been observed. Thus, the neurodegeneration in the basal forebrain in AD is aggravated by a reduction in signaling from TrkA receptors coupled with apoptotic signaling by proNGF binding to p75 (see Section 2.2). Animal studies and clinical trials of NGF gene delivery show promise in curtailing neuronal apoptosis in Alzheimer's disease or animal models. However, the CBF in some patients demonstrated a trophic response of immature neuritic processes, i.e. neurite outgrowth where it was not needed or useful. Adult brains with AD possessing an established axonal network may be adversely affected by this type of aberrant neuritogenesis. Survival support for existing neurons is preferable without inducing *de novo* connections that might be dysfunctional. A key goal for future intervention of this type is to promote viability of specific neurons without causing neuritic or axonal overgrowth.

The possibility and potential of designer growth factors has been highlighted in this review. Step-wise mutagenesis of NGF led to the generation of survival-selective muteins that are potentially therapeutic lead candidates for Alzheimer Disease or other neurodegenerative disorders. Two mechanism-selective recombinant NGF muteins show a marked difference in the ratio of survival to neuritogenesis in several assays, including signaling through the Akt survival pathway. Thus, in principle one can separate intracellular signaling pathways for a receptor via modifications to its ligand. Successful parallel studies with molecular engineering of insulin and TNFα support this viewpoint. Structural studies of other receptor systems, e.g., EGF, have provided a logical, molecular basis for understanding how these signals may be separately activated. Progress with small molecule mimetics of NGF that are agonists show some of the same receptor- and signaling- selectivity that receptor- or signal-selective muteins of the parent protein do. The future should provide major advances in this exciting area of improving upon nature and developing novel treatments for AD. Coupling of designer neurotrophins with improved delivery to the brain provides great promise.

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10. Nomenclature

7-84-103, NGF mutein, F7A/H84A/R103A
Aβ, beta amyloid
AD, Alzheimer's disease
APP, amyloid precursor protein
Akt, a ser-thr kinase (also PKB)
BDNF, brain derived neurotrophic factor
BBB, blood brain barrier
CBF, cholinergic basal forebrain
ECD, extracellular domain
EGF, epidermal growth factor
EGFR, EGF receptor
GSK3b, glycogen synthase kinase 3b
ICD, intracellular domain
IGF-1, insulin like growth factor 1
JNK, c-Jun N-terminal kinase
KKE, K32A/K34A/E35A NGF mutein
KKE/7-84-103, hextuple mutein, K32A/K34A/E35A/F7A/H84A/R103A NGF mutein
MAPK, mitogen-activated protein kinase
NF-κB, Nuclear factor kappa-light-chain-enhancer of activated B cells
NGF, nerve growth factor (β-subunit)
NT-3, neurotrophin 3
NT-4, neurotrophin 4
p75, common neurotrophin receptor
PC12, pheochromocytoma 12 cell line
PI3K, phosphoinositide 3-kinase
PLCγ, phospholipase C gamma
proNGF, precursor form of NGF
TNFα, tumor necrosis factor alpha
Trk, tropomyosin related kinase
Δ9/13, NGF mutein with residues 9 through 13 deleted

11. References

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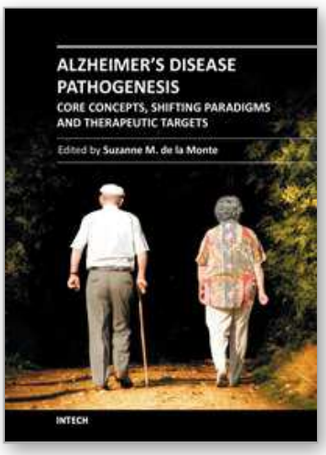

Alzheimer's Disease Pathogenesis-Core Concepts, Shifting Paradigms and Therapeutic Targets

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Alzheimer's Disease Pathogenesis: Core Concepts, Shifting Paradigms, and Therapeutic Targets, delivers the concepts embodied within its title. This exciting book presents the full array of theories about the causes of Alzheimer's, including fresh concepts that have gained ground among both professionals and the lay public. Acknowledged experts provide highly informative yet critical reviews of the factors that most likely contribute to Alzheimer's, including genetics, metabolic deficiencies, oxidative stress, and possibly environmental exposures. Evidence that Alzheimer's resembles a brain form of diabetes is discussed from different perspectives, ranging from disease mechanisms to therapeutics. This book is further energized by discussions of how neurotransmitter deficits, neuro-inflammation, and oxidative stress impair neuronal plasticity and contribute to Alzheimer's neurodegeneration. The diversity of topics presented in just the right depth will interest clinicians and researchers alike. This book inspires confidence that effective treatments could be developed based upon the expanding list of potential therapeutic targets.

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