

OECD Series on Adverse Outcome Pathways No. 8

Adverse Outcome Pathway on chronic binding of antagonist to N-methyl-D-aspartate receptors during brain development leading to neurodegeneration with impairment in learning and memory in aging

Florianne Tschudi-Monnet,

Rex FitzGerald

https://dx.doi.org/10.1787/95f569ad-en

OECD

Adverse Outcome Pathway on chronic binding of antagonist to N-methyl-D-aspartate receptors during brain development leading to neurodegeneration with impairment in learning and memory in aging

Series on Adverse Outcome Pathways No. 8

Foreword

This Adverse Outcome Pathway (AOP) on chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leading to neurodegeneration with impairment in learning and memory in aging, has been developed under the auspices of the OECD AOP Development Programme, overseen by the Extended Advisory Group on Molecular Screening and Toxicogenomics (EAGMST), which is an advisory group under the Working Group of the National Coordinators for the Test Guidelines Programme (WNT). The AOP has been reviewed internally by the EAGMST, externally by experts nominated by the WNT, and has been endorsed by the WNT and the Working Party on Hazard Assessment (WPHA) in June 2018.

Through endorsement of this AOP, the WNT and the WPHA express confidence in the scientific review process that the AOP has undergone and accept the recommendation of the EAGMST that the AOP be disseminated publicly. Endorsement does not necessarily indicate that the AOP is now considered a tool for direct regulatory application.

The Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology agreed to declassification of this AOP in September 2018.

This document is being published under the responsibility of the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology.

The outcome of the internal and external reviews are publicly available respectively in the AOP Wiki and the eAOP Portal of the AOP Knowledge Base at the following links: [internal review] [external review].

Table of contents

Foreword **1**

Adverse Outcome Pathway on Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leading to neurodegeneration with impairment in learning and memory in aging **5**

Short Title: Binding of antagonist to NMDARs can lead to neuroinflammation and neurodegeneration 5
Authors 5

Abstract **6**

Graphical Representation **7**

Summary of the AOP **8**

Molecular Initiating Events (MIE), Key Events (KE), Adverse Outcomes (AO) 8
Key Event Relationships 8
Stressors 8

Overall Assessment of the AOP **9**

Domain of Applicability 10
Life Stage Applicability 10
Taxonomic Applicability 10
Essentiality of the Key Events 10
Weight of Evidence Summary 12
1. Concordance of dose-response and temporal concordance between KEs and the AO 12
2. Strength, consistency and association of AO and MIE 14
3. Biological Plausibility, and empirical support 15
Quantitative Consideration 17

Considerations for Potential Applications of the AOP (optional) **18**

References **19**

Appendix 1: List of MIE(s), KE(s) and AO(s) in the AOP **24**

List of MIE(s) in the AOP 24
Event: 201: Binding of antagonist, NMDA receptors 24
List of KE(s) in the AOP 31
Event: 195: Inhibition, NMDARs 31
Event: 52: Decreased, Calcium influx 35
Event: 381: Reduced levels of BDNF 39
Event: 55: N/A, Cell injury/death 44
Event: 188: N/A, Neuroinflammation 49
List of AO(s) in the AOP 55
Event: 352: N/A, Neurodegeneration 55
List of AO(s) in the AOP 59
Event: 341: Impairment, Learning and memory 59

Appendix 2: List of Key Event Relationships (KERs) in the AOP **66**

List of Adjacent Key Event Relationships 66
Relationship: 229: Binding of antagonist, NMDA receptors leads to Inhibition, NMDARs 66
Relationship: 213: Inhibition, NMDARs leads to Decreased, Calcium influx 70
Relationship: 347: Decreased, Calcium influx leads to BDNF, Reduced 77
Relationship: 353: BDNF, Reduced leads to N/A, Cell injury/death 81
Relationship: 365: N/A, Cell injury/death leads to N/A, Neuroinflammation 87
Relationship: 208: N/A, Neuroinflammation leads to N/A, Neurodegeneration 93
Relationship: 207: N/A, Neurodegeneration leads to N/A, Neuroinflammation 99
Relationship: 1069: N/A, Neurodegeneration leads to Impairment, Learning and memory 102

Adverse Outcome Pathway on Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leading to neurodegeneration with impairment in learning and memory in aging

Short Title: Binding of antagonist to NMDARs can lead to neuroinflammation and neurodegeneration

Authors

Florianne Tschudi-Monnet, Department of Physiology, University of Lausanne, Switzerland, and Swiss Center for Applied Human Toxicology (SCAHT)

Rex FitzGerald, SCAHT, Universität Basel, Missionsstrasse 64, CH-4055 Basel

Acknowledgments: The authors greatly acknowledged the contribution of Drs Anna Price and Magdalini Sachana who prepared the MIE and KE1-KE4 as well as the related KERs of this AOP.

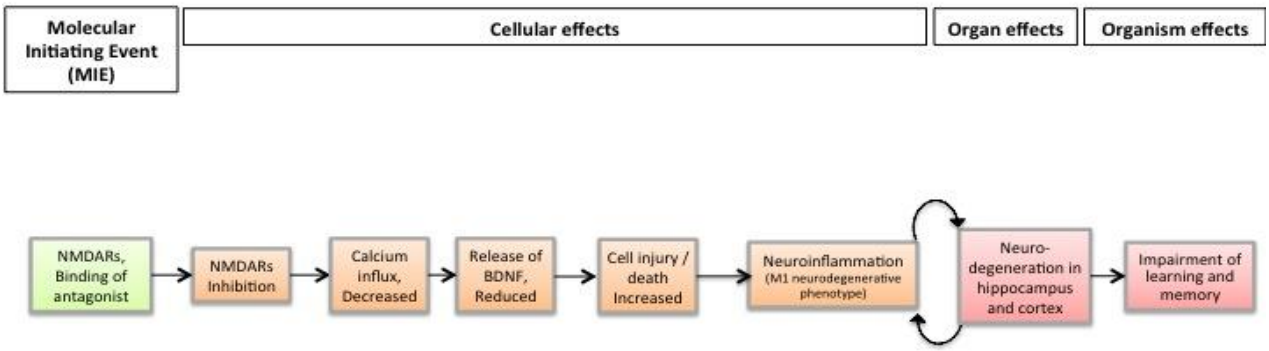
Anna Price, Joint Research Centre Institute for Health and Consumer Protection Systems Toxicology Unit Via E. Fermi 2749 - 21020 - Ispra (VA) -Italy

Magdalini Sachana, Joint Research Centre Institute for Health and Consumer Protection Systems Toxicology Unit Via E. Fermi 2749 - 21020 - Ispra (VA) -Italy

Abstract

This AOP links chronic NMDA receptors inhibition during brain development to neurodegeneration in hippocampus and cortex with amyloid plaque deposition and tau hyperphosphorylation, and impairment of learning and memory, which are considered as hallmark of Alzheimer's disease. It makes use of some KEs and KERs from AOP 13 and introduces Neuroinflammation as KE, which is involved in several neurodegenerative diseases. This AOP is based on the hypothesis of Landrigan and coworkers (2005) proposing an early origin of neurodegenerative diseases in later life. The chemical initiator used in this AOP for the empirical support is lead (Pb). In adults, cumulative lifetime Pb exposure is also associated with decline in cognition, suggesting that long-term exposure during development or occupational exposure increases the risk to develop neurodegenerative disease. The long latency period between exposure and late-onset of effects gives a very broad life-stage applicability. The gap of knowledge is mainly due to limited quantitative evaluations.

Graphical Representation



Summary of the AOP

Molecular Initiating Events (MIE), Key Events (KE), Adverse Outcomes (AO)

Sequence	Type	Event ID	Title	Short name
1	MIE	201	Binding of antagonist, NMDA receptors	Binding of antagonist, NMDA receptors
2	KE	195	Inhibition, NMDARs	Inhibition, NMDARs
3	KE	52	Decreased, Calcium influx	Decreased, Calcium influx
4	KE	381	Reduced levels of BDNF	BDNF, Reduced
5	KE	55	N/A, Cell injury/death	N/A, Cell injury/death
6	KE	188	N/A, Neuroinflammation	N/A, Neuroinflammation
7	AO	352	N/A, Neurodegeneration	N/A, Neurodegeneration
8	AO	341	Impairment, Learning and memory	Impairment, Learning and memory

Key Event Relationships

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
Binding of antagonist, NMDA receptors	adjacent	Inhibition, NMDARs	High	
Inhibition, NMDARs	adjacent	Decreased, Calcium influx	Moderate	
Decreased, Calcium influx	adjacent	Reduced levels of BDNF	Low	
Reduced levels of BDNF	adjacent	N/A, Cell injury/death	Low	
N/A, Cell injury/death	adjacent	N/A, Neuroinflammation	Moderate	
N/A, Neuroinflammation	adjacent	N/A, Neurodegeneration	Low	
N/A, Neurodegeneration	adjacent	N/A, Neuroinflammation	Moderate	
N/A, Neurodegeneration	adjacent	Impairment, Learning and memory	High	

Stressors

Name	Evidence
Lead	

Overall Assessment of the AOP

The aim of this AOP is to capture the KEs and KERs that occur after chronic binding of antagonist to NMDA receptors in neurons of hippocampus and cortex during brain development and that lead to neurodegeneration with impairment in learning and memory in later life. Neurodegenreation with accumulation of amyloid plaques and hyperphosphorylated tau, as well as cognitive deficit are associated with Alzheimer-type neurodegeneration. Currently, the hypothesis of Landrigan et al., (2005) of developmental origins of neurodegenerative diseases has been demonstrated in monkeys, in rats, mice and in zebrafish following Pb treatment (Zawia and Basha, 2005; Basha and Reddy, 2010; Bihaqi et al., 2014a; Bihaqi et al., 2014b ; Lee and Freeman, 2014). There is strong agreement that Alzheimer's disease is progressive and that neurodegeneration is occuring mainly in hippocampus and cortex, associated with cognitive deficits (Schoemaker et al., 2014). This AOP uses the MIE and several KEs of the AOP 13 entitled "Binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities", with an additional KE: neuroinflammation and two AOs: an AO at the organ level: Neurodegeneration in hippocampus and cortex and an AO at the organism level: Impairment of learning and memory. Impairment of learning and memory is the same AO as in AOP 13, but the point is that this AO is detected when the brain is aging, and it is due to neurodegeneration with accumulation of amyloid peptides and tau hyperphosphorylation. The recent review by Tartatglione and coworkers (2016) is a very good summary of the challenges and experimental studies described in this AOP.

Developmental Pb exposure has adverse effects on cognitive functioning that can persist into adulthood and may be exacerbated with aging (Schneider et al., 2013). Such delayed effects may be due to epigenetic effects of developmental Pb exposure on DNA methylation mediated at least in part through dysregulation of methyltransferases observed often at the lowest level of exposure (Schneider et al., 2013). In addition, key neurodevelopmental events, such as neural differentiation, cell migration and network formation may be modulated by Pb exposure, predisposing the brain for alterations in higher brain functions, such as learning and memory, and this at different ages (for review, see Aschner et al., 2017). The fact that neuroinflammation triggered during early brain development was shown to cause Alzheimer-like pathology when aging (Krstic et al., 2012), suggests that chronic neuroinflammation may play a causal role in cognitive decline in aging. A recent report described a mechanistic link between chronic inflammation and aging microglia; and a causal role of aging microglia in neurodegenerative cognitive deficits: A sirtuin 1 (SIRT1) deficiency was observed in aging microglia, leading to a selective activation of IL1-b transcription mediated through hypomethylation of IL-1b proximal promoter exacerbating aging or tau-associated cognitive deficits (Cho et al., 2015). Taken together, these data suggest that Pb-induced neuroinflammation during brain development may underlie the delayed effects on cognitive deficits in aging, as depicted in the proposed AOP.

Domain of Applicability

Life Stage Applicability

Life Stage	Evidence
During brain development	

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	Low	NCBI
Monkey	Monkey	High	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	Moderate	NCBI
zebrafish	Danio rerio	Moderate	NCBI

This AOP is not sex dependent. Regarding the life stage applicability, MIE induced during brain development can have consequences when brain is aging, according to the hypothesis proposed by Landrigan and coworkers (2005). However, it is also possible that the AO does not depend exclusively on developmental exposure, since cumulative occupational exposure also decreased cognitive functions in aging (Stewart et al., 2006).

Essentiality of the Key Events

Table: Essentiality of KEs

Support for Essentiality of KEs	**Defining Question** Are downstream KEs and/or the AO prevented if an upstream KE is blocked?	**High (Strong)** Direct evidence from specifically designed experimental studies illustrating essentiality for at least one of the important KEs (e.g. stop/reversibility studies, antagonism, knock out models, etc.)	**Moderate** Indirect evidence that sufficient modification of an expected modulating factor attenuates or augments a KE leading to increase in KE down or AO	**Low (Weak)** No or contradictory experimental evidence of the essentiality of any of the KEs
KE1 NMDARs inhibition	STRONG	Activation of NMDAR results in LTP, which is related to increase synaptic strength and memory formation in hippocampus (Johnston et al., 2009).		
KE2 Calcium influx decreased	STRONG	In CNS, many intracellular responses to modified calcium level are mediated by calcium/calmoduline-regulated protein kinases (Wayman et al., 2008). Mice with a mutation of calmoduline kinase II, which is abundantly found in hippocampus, have shown spatial learning impairment (Silva et al., 1992)		
KE3 Release of BDNF, reduced	STRONG	BDNF serves essential function in synaptic plasticity (Poo, 2001) and is crucial for learning and memory processes (Lu et al., 2008). Precursor form of BDNF and		

		mature BDNF are decreased in the preclinical stages of Alzheimer's disease (Peng et al., 2005)
KE4 Cell Injury/death, increased	STRONG	Several studies dealing with postnatal administration of NMDAR antagonists such as MK 801, ketamine or ethanol have shown a devastating cell apoptotic degeneration in several brain areas of animal models resulting in learning deficits (Creeley and Olney, 2013)
KE5 Neuroinflammation	MODERATE	Rationale: Rats treated with Pb from PND 24 to 80 showed a neuroinflammatory response associated with neuronal death in hippocampus and LTP impairment. These effects were significantly reversed by administration of minocycline, an antibiotic known to block microglial reactivity (Liu et al., 2012), demonstrating the essentiality of neuroinflammation for neurodegeneration in hippocampus and impairment of memory processes. In addition, the fact that neuroinflammation triggered during brain development by a systemic immune challenge caused Alzheimer's like pathology (Krstic et al., 2012), showed the central role of neuroinflammation in this pathology. In addition, in a mouse model of Alzheimer's disease, the blockade of microglial cell proliferation and the shifting of the microglial inflammatory profile to an anti-inflammatory phenotype by inhibiting the colony-stimulating factor 1 receptor on microglial cells, prevented synaptic degeneration and improved cognitive functions (Olmos-Alonso et al., 2016). This latter experiment has not been done during brain development. But the hypothesis is that a chronic neuroinflammation during a prolonged period increased the risk to develop an Alzheimer's neurodegenerative disease in aging (Krstic and Knuesel, 2013). However, as other mechanisms such epigenetic modifications can lead to accumulation of amyloid plaques- and tau hyperphosphorylation-related neurodegeneration, and due to some inconsistencies of anti-inflammatory treatments as protection against the neurodegenerative process, the essentiality of Neuroinflammation was considered as moderate.
AO (at organ level) Neurodegeneration in hippocampus and cortex	STRONG	Several studies descibed Pb-induced accumulation of amyloid peptides and hyperphosphorylated and Pb-induced cell injury/deathin hippocampus or decrease in hippocampal volume, what are all well accepted landmarks of Alzheimer's pathology (Lloret et al., 2015). As described in AOP 48, neurodegeneration can lead to "Decreased neuronal network function" which in turn leads to "impairment of learning and memory", which is also considered as a hallmark of Alzheimer's pathology (Schoemaker et al., 2014). However, there is some controversy about the relationship between increased accumulation of amyloid plaques and increased cognitive deficits: Lichtenstein and coworkers (2010) described that accumulation of amyloid plaques reaches a plateau, whereas a temporal relationship is observed between increased microglial

		activation, widespread degeneration (decreased hippocampal volume) and increased cognitive deficits. Therefore the essentiality for accumulation of amyloid and tau to cognitive deficits should be considered as moderate. But, as cell injury/death in hippocampus and cortex or decrease in hippocampal volume due to widespread neurodegeneration is strongly associated to impairment in learning and memory, the essentiality of this KE has been rated as strong.
AO (at organism level) Impairment of learning and memory	STRONG	Neurodegenerative diseases are complex and multifactorial, depend on gene-environment interactions, and have a slow temporal evolution (Sherer et al., 2002; Steece-Collier et al., 2002; Tsang and Soong, 2003); Mutter et al., 2004). A direct association between Pb exposure during brain development and Alzheimer's pathology is not supported by epidemiological studies. However, two studies reported that past adult exposure is linked with neurodegeneration (Stewart et al., 2006) and decline in cognitive function (Schwartz et al., 2000), effects which were observed long after exposure ceases. Tibia lead levels were good predictors of these delayed effects. Another study showed an association between lead exposure early in life with cognitive and behavioral consequences in early adulthood (Agency for toxic substances, 1997). Despite the lack of specific epidemiological evidence, the principle of delayed effects occuring long after exposure, as well as strong evidence from experimental studies (for review, see Chin-Chan et al., 2015) suggest that long-term exposure to environmental toxicants such as Pb during brain development or exposure later in life can be considered as a risk factor for the development of neurodegenerative diseases in aging.

Weight of Evidence Summary

1. Concordance of dose-response and temporal concordance between KEs and the AO

It is difficult to analyse the dose-response relationships between the different KEs, (i) because of the long temporal delay between MIE and AOs; (ii) because no study has analysed them simultaneously, and (iii) because of the difficulties in extrapolating *in vitro* to *in vivo* data. As the apical KEs and AO occur and can be measured years after exposure, even when Pb blood level has returned to normal, measurement of bone Pb content has been proposed as a measurement of historical Pb exposure in adults (Bakulski et al., 2012, 2014). The following table gives an overview of the doses/concentrations and exposure duration at which the different KEs were measured.

KE1	KE2	KE3	KE4	K5	AO at organ level	AO at organism level
NMDAR inhibition	**Calcium influx, decreased**	**BDNF release, decreased**	**Cell injury/death**	**Neuroinflammation**	**Neurodegeneration with amyloid plaques and tau hyperphosphorylation**	**Impairment of learning and memory**
Pb 2.5-5 mM acute inhibits NMDAR whole cell and channel current in hippocampal neurons (Alkondon et al., 1990)	Pb 100 nM 1h-24h decrease Ca2+ in embryonic rat hippocampal neurons (Ferguson et al., 2000)	No direct evidence	Pb 2mM in drinking water 3 weeks before mating till weaning (PND 21) resulting in at PND 21 Pb blood 108.8 mg/L Pb hippoc. 0.253 mg/g at PND 91 Pb blood 39.27 mg/L Pb hippoc. 0.196 mg/g about 35% decrease in synapses in hippocampus about 30% decrease of hippocampal neurons (Xiao et al., 2014)	*In vivo* 0.22 ppm (together with As and Cd) from gestational day 5 till day 180 in adulthood: IL-1b, TNF-a, IL-6 increased 2x Ashok et al., 2015 Rats exposed to Pb 100 ppm for 8 weeks (from PND 24 to 80) caused at the end of treatment microglial activation in hippocampus (Liu et al., 2012). *In vitro* 10^{-6}-10^{-4} M for 10 days in 3D cultures of fetal rat brain cells microglial and astrocyte reactivities (Zurich et al., 2002) co-cultures of hippocampal neurons with microglial cells treated with Pb (50 micomol/L for 48h) caused microglial activation and upregulation of IL-1beta, TNF-alpha and i_NOS (Liu et al., 2012)	Monkeys exposed to Pb 1.5 mg/kg/day from birth to 400 days at 23 years of age Tau accumulation Overexpression of amyloid-beta protein precursor and of amyloid-beta enhanced pathologic neurodegeneration (Bihaqi et al., 2011; Bihaqi and Zawia, 2013). Mice exposed to Pb 0.2% in drinking water from PND 1-20 or from PND 1-20 + From 3-7 months at 700 days of age elevated protein and mRNA for tau and aberrant site-specific tau hyperphosphorylation (Bihaqi et al., 2014a). Human Tg-SWDI APP transgenic mice, PB 50 mg/kg by gavage for 6 weeks exhibit increase AB in CSF, cortex and hippocampus and increased amyloid plaque load (Gu et al., 2012). Rats exposed to Pb 100 ppm for 8 weeks (from PND 24 to 80) caused at the end of treatment neuronal death in hippocampus (Liu et al., 2012).	Mice exposed to Pb 0.2% in drinking water from PND 1-20 or from PND 1-20 and from 3-7 months. Tested at 700 days of age Decrease in cognitive functions (Morris water maze, Y maze testing for spatial memory and memory, a hippocampal formation-dependent task) (Bihaqi et al., 2014b). Rats exposed to Pb 100 ppm for 8 weeks (from PND 24 to 80) reduced hippocampal LTP level at the end of the treatment

						(Liu et al., 2012). Human Tg-SWDI APP transgenic mice , PB 50 mg/kg by gavage for 6 weeks showed an impaired spatial learning (Gu et al., 2012)

2. Strength, consistency and association of AO and MIE

The accepted molecular mechanism of action of the chemical initiator Pb is inhibition of NMDARs (Alkondon et al., 1990; Gavazzo et al., 2001, 2008; Guilarte et al., 1992; Omelchenko et al., 1997) and several experimental studies in rat, monkey and zebrafish linked chronic exposure to Pb during brain development to Alzheimer's-like neurodegeneration with cognitive deficits (Zawia and Basha, 2005; Basha and Reddy, 2010; Bihaqi et al., 2014a; Bihaqi et al., 2014b ; Lee and Freeman, 2014). This AOP is defined by a single environmental chemical, Pb. However, other NMDAR antagonists used as general anesthetics (MK 801, phenylcyclidine, ketamine) applied during brain development may also lead to functional impairments in cognitive domains relevant to memory. The effects of these anesthetics on brain function appear to have a delayed onset, and can be very long-lasting if not permanent. In general, longer durations, higher concentrations and longer or repeated exposures tend to exacerbate impairments (for review, see Walters and Paule, 2017). The mechanisms underlying anesthetic-induced neurotoxicity are unclear, but several hypotheses have been proposed: impairment of mitochondrial integrity and function, dysregulation of intracellular calcium and neuroinflammation have all been implicated (Lei et al., 2012). Some of these mechanisms are common to the KEs described in this AOP, suggesting that such delayed effects on memory processes can be a general consequence of developmental brain exposure to NMDAR inhibitors. However, no studies have yet reported that these other NMDAR inhibitors cause amyloid plaque deposition or tau hyperphosphorylation associated with Alzheimer-like neurodegeneration when aging.

Interestingly, memantine, a NMDAR antagonist used in the treatment of Alzheimer's disease, was shown to improve cognitive functions (for review, see Dekundy, 2006). This might be considered as a discrepancy with the described AOP considering Pb as an antagonist of NMDAR and its potential risk to cause cognitive deficits and amyloid plaque accumulation, which are hallmarks of Alzheimer's disease. However, memantine antagonism of NMDAR is quite different (low affinity and voltage-dependent) and the window of exposure differs completely, since memantine is applied in aged patients when the disease has broken out; whereas the risk of delayed neurodegeneration described in this AOP is due to NMDAR inhibition during brain development.

3. Biological Plausibility, and empirical support

Support for Biological Plausibility of KERs	**Defining Question** Is there a mechanistic (i.e. structural or functional) relationship between KE up and KE down consistent with established biological knowledge?	**High /Strong** Extensive understanding of the KER based on extensive previous documentation and broad acceptance	**Moderate** The KER is plausible based on analogy to accept biological relationship but scientific understanding is not completely established	**Low/weak** There is empirical support for a statistical association between KEs but the structural or functional relationship between them is not understood
MIE to KE inhibition of NMDARs		Extensive understanding Limited conflicting data		
KE NMDAR inhibition to KE calcium influx, decreased		Extensive understanding Limited conflicting data		
KE calcium influx, decreased to KE release of BDNF, decreased		Extensive understanding Limited conflicting data		
KE release of BDNF, decreased to KE Cell Injury/death		Extensive understanding Limited conflicting data		
KE Cell injury/death to KE Neuroinflammation			The general mechanisms linking cell injury/death to neuroinflammation is well accepted. However, it is mainly descibed in adult brain. However, a neuroinflammatory response was found following Pb exposure of 3D cultures during synaptogenesis and myelination (Zurich et al., 2002). A controversy exists about apoptosis and neuroinflammation, but some empirical evidences has been provided. The fact that cell injury/deat leads to neuroinflammation and	

			that neuroinflammation leads to neurodegeneration is known as avicious circle and is involved in neurodegenerative diseases, suggesting that neuroinflammation exacerbates the neurodegenerative process (Griffin et al., 1998; 2006)	
KE Neuroinflammation to AO Neurodegeneration in Hippocampus and cortex	In adult, the early involvement of neuroinflammation in the neurodegenerative process is widely accepted. In immature brain, one study in mice link gestational induction of neuroinflammation to late neurodegeneration with accumulation of aberrant amyloid and tau (Kristic et al., 2012).		There is *in vitro* experimental data following Pb exposure linking neuroinflammation to extensive neuronal death in immature cells. *In vivo*, There are several studies linking early Pb exposure to late neurodegeneration in several species. However, the mechanisms involved is epignenetic modifications of genes involved in the amyloid cascade. Such epigenetic modifications may be due to ROS released by the neuroinflammatory process (Bolin et al., 2006). Therefore the link may be indirect and needs further analyses.	
AO Neurodegeneration in hippocampus and cortex to KE Neuroinflammation	Concept of vicious circle where neuroinflammation lead to neurodegeneration and vice versa (Griffin et al., 1998, 2006)			There are no specific empirical data for the chemical initiator Pb.
AO Neurodegeneration in hippocampus and cortex to AO Impairment of		The role of hippocampus in memory processes is well accepted. Alterations of LTP in hippocampus of rats		

learning and memory		exposed to Pb has been described (Liu et al., 2012), as well as preferential accumulation of hyperphosphorylated tau in frontal cortex of mice exposed during development to Pb. These mice exhibited cognitive deficit when aging (Bihaqi et al., 2014b).		

Quantitative Consideration

With an Adverse Outcome occurring after such a long delay after the MIE, it is extremely difficult to make a quantitative link, since the AO can occur when serum Pb levels have returned to normal. Bakulski and coworkers (2012) therefore proposed measuring Pb bone content as an index of historical Pb exposure. Similarly, Schwartz and coworkers (2000) showed that tibia Pb levels were good predictors of delayed cognitive decline of former organolead workers. Thus, Pb blood level is rather representative of acute exposure, whereas Pb bone levels represent long-term accumulation (Dorsey et al., 2006).

Regarding the KER "cell injury/death to neuroinflammation", it is accepted that neuronal injury may be sufficient to trigger a neuroinflammatory response. But, because of the neuroprotective or neuroreparative potential of neuroinflammation, it is possible that the consequences of neuroinflammation will be in a first step positive, with microglia expressing the M2 phenotype. After an exposure arrest and a temporal delay (Sandström et al., 2014), or in the presence of cell death (Nakajima and Kohsaka, 2004; Hanish and Kettenmann, 2007), microglia can acquire the M1 neurodegenerative phenotype. Therefore, it is rather the qualitative phenotype of neuroinflammation that will induce neurodegeneration. However, a possible correlation of increased microglial reactivity, measured by PET, and a decrease in hippocampal volume, measured by MRI, suggests, in advanced Alzheimer's disease, a possible link between the intensity of neuroinflammation and the neurodegenerative consequences (Lichtenstein et al., 2010).

Considerations for Potential Applications of the AOP (optional)

This AOP aims at giving a conceptual framework to mechanistically understand an apical hazard, which can occur long after initial exposure; this hazard is not captured in standard regulatory neurotoxicity testing.

The KE "neuroinflammation", which is shared with other AOPs, appears to play an early and central role in the neurodegenerative process (Eikelenboom et al., 2000; Whitton, 2007; Krstic et al., 2012). Neuroinflammation is observed in most neurodegenerative diseases including Alzheimer's disease (Whitton, 2007; Tansey and Goldberg, 2009; Niranjan, 2014 ; Verkhratsky et al., 2014). Neuroinflammation can also be triggered by several classes of toxicants (Monnet-Tschudi et al., 2007). Any toxicant able to trigger a neuroinflammatory response expressing the neurodegenerative phenotype should be considered as a risk factor for neurodegenerative diseases. Therefore, testing for toxicant-induced neuroinflammation should be used as an endpoint in regulatory toxicology. The standard neurotoxicity testing does not require measurement of any marker of neuroinflammation, except for fuel additives, where testing for a potential increase in glial fibrillary acidic protein (GFAP), as marker of astrocyte reactivity, is mandatory according to US EPA (40 CFR 79 67).

The evolution of regulation towards mechanistically-driven approaches for supporting hazard identification implies also the development of *in vitro* testing. Three-dimensional cultures, prepared from fetal rat brain cells, exhibiting an histotypic organisation comprising all types of brain cells (specifically microglial cells and astrocytes, as effector cells of neuroinflammation) and allowing long-term maintenance for repeated exposure and for studying the evolution of neuroinflammatory phenotypes, are already available (Alépée et al., 2014; Monnet-Tschudi et al., 2007 ; Sandström et al., 2014). Similar 3D cultures prepared from human pluripotent stem cells are in development (Schwartz et al., 2015; Sandström et al., 2017).

References

ATSDR 2007. Toxicological Profile for Lead. U.S. Agency for Toxic Substances and Disease Registry, August 2007.

Alépée N, Bahinski A, Daneshian M, De Wever B, Fritsche E, Goldberg A, et al. 2014. State-of-the-art of 3D cultures (organs-on-a-chip) in safety testing and pathophysiology. Altex 31(4): 441-477.

Alkondon M, Costa AC, Radhakrishnan V, Aronstam RS, Albuquerque EX. 1990. Selective blockade of NMDA-activated channel currents may be implicated in learning deficits caused by lead. FEBS Lett 261(1): 124-130.

Aschner M, Ceccatelli S, Daneshian M, Fritsche E, Hasiwa N, Hartung T, et al. 2017. Reference compounds for alternative test methods to indicate developmental neurotoxicity (DNT) potential of chemicals: example lists and criteria for their selection and use. Altex 34(1): 49-74.

Ashok A, Rai NK, Tripathi S, Bandyopadhyay S. 2015. Exposure to As-, Cd-, and Pb-mixture induces Abeta, amyloidogenic APP processing and cognitive impairments via oxidative stress-dependent neuroinflammation in young rats. Toxicol Sci 143(1): 64-80.

Bakulski KM, Rozek LS, Dolinoy DC, Paulson HL, Hu H. 2012. Alzheimer's disease and environmental exposure to lead: the epidemiologic evidence and potential role of epigenetics. Curr Alzheimer Res 9(5): 563-573.

Bakulski, K.M., Park, S.K., Weisskopf, M.G., Tucker, K.L., Sparrow, D., Spiro, A., 3rd, Vokonas, P.S., Nie, L.H., Hu, H., Weuve, J., 2014. Lead exposure, B vitamins, and plasma homocysteine in men 55 years of age and older: the VA normative aging study. Environ Health Perspect 122(10), 1066-1074.

Basha R, Reddy GR. 2010. Developmental exposure to lead and late life abnormalities of nervous system. Indian journal of experimental biology 48(7): 636-641.

Bihaqi SW, Huang H, Wu J, Zawia NH. 2011. Infant exposure to lead (Pb) and epigenetic modifications in the aging primate brain: implications for Alzheimer's disease. J Alzheimers Dis 27(4): 819-833.

Bihaqi SW, Zawia NH. 2013. Enhanced taupathy and AD-like pathology in aged primate brains decades after infantile exposure to lead (Pb). Neurotoxicology 39: 95-101.

Bihaqi SW, Bahmani A, Adem A, Zawia NH. 2014a. Infantile postnatal exposure to lead (Pb) enhances tau expression in the cerebral cortex of aged mice: relevance to AD. Neurotoxicology 44: 114-120.

Bihaqi SW, Bahmani A, Subaiea GM, Zawia NH. 2014b. Infantile exposure to lead and late-age cognitive decline: relevance to AD. Alzheimer's & dementia: the journal of the Alzheimer's Association 10(2): 187-195.

Bolin CM, Basha R, Cox D, Zawia NH, Maloney B, Lahiri DK, et al. 2006. Exposure to lead and the developmental origin of oxidative DNA damage in the aging brain. Faseb J 20(6): 788-790.

Chin-Chan, M., Navarro-Yepes, J., Quintanilla-Vega, B., 2015. Environmental pollutants as risk factors for neurodegenerative disorders: Alzheimer and Parkinson diseases. Front Cell Neurosci 9, 124.

Cho SH, Chen JA, Sayed F, Ward ME, Gao F, Nguyen TA, et al. 2015. SIRT1 deficiency in microglia contributes to cognitive decline in aging and neurodegeneration via epigenetic regulation of IL-1beta. J Neurosci 35(2): 807-818.

Creeley CE, Olney JW. (2013) Drug-Induced Apoptosis: Mechanism by which Alcohol and Many Other Drugs can Disrupt Brain Development. Brain Sci. 3: 1153–1181.

Dekundy A.2006. Coadministration of memantine with Acetylcholinesterase Inhibitors: Preclinical and Clinical Evidence. In: Toxicology of Organophosphate and Carbamate Compounds. Gupta RC, editor. Elsevier. Amsterdam. Chap. 4. pp 35-46.

Dorsey CD, Lee BK, Bolla KI, Weaver VM, Lee SS, Lee GS, et al. 2006. Comparison of patella lead with blood lead and tibia lead and their associations with neurobehavioral test scores. Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine 48(5): 489-496.

Eikelenboom P, Rozemuller AJ, Hoozemans JJ, Veerhuis R, van Gool WA. 2000. Neuroinflammation and Alzheimer disease: clinical and therapeutic implications. Alzheimer Dis Assoc Disord 14 Suppl 1: S54-61.

Ferguson C, Kern M, Audesirk G. 2000. Nanomolar concentrations of inorganic lead increase Ca2+ efflux and decrease intracellular free Ca2+ ion concentrations in cultured rat hippocampal neurons by a calmodulin-dependent mechanism. Neurotoxicology 21(3): 365-378.Gavazzo P, Gazzoli A, Mazzolini M, Marchetti C. 2001. Lead inhibition of NMDA channels in native and recombinant receptors. Neuroreport 12(14): 3121-3125.

Gavazzo P, Zanardi I, Baranowska-Bosiacka I, Marchetti C. 2008. Molecular determinants of Pb2+ interaction with NMDA receptor channels. Neurochem Int 52(1-2): 329-337.

Griffin WST, Sheng JG, Royston MC, Gentleman SM, McKenzie JE, Graham DI, et al. 1998. Glial-neuronal interactions in Alzheimer's disease: The potential role of a 'cytokine cycle' in disease progression. Brain Pathol 8: 65-72.

Griffin WS. 2006. Inflammation and neurodegenerative diseases. Am J Clin Nutr 83(2): 470S-474S.

Gu H, Robison G, Hong L, Barrea R, Wei X, Farlow MR, et al. 2012. Increased beta-amyloid deposition in Tg-SWDI transgenic mouse brain following *in vivo* lead exposure. Toxicol Lett 213(2): 211-219.

Guilarte TR, Miceli RC. 1992. Age-dependent effects of lead on [3H]MK-801 binding to the NMDA receptor-gated ionophore: *in vitro* and *in vivo* studies. Neurosci Lett 148(1-2): 27-30.

Hanisch UK, Kettenmann H. 2007. Microglia: active sensor and versatile effector cells in the normal and pathologic brain. Nat Neurosci 10(11): 1387-1394.

Johnstone AFM, Gross GW, Weiss D, Schroeder O, Shafer TJ. 20. Use of microelectrode arrays for neurotoxicity testing in the 21st century Neurotoxicology 31: 331-350.

Krstic D, Madhusudan A, Doehner J, Vogel P, Notter T, Imhof C, Manalastas A, Hilfiker M, Pfister S, Schwerdel C, et al. 2012. Systemic immune challenges trigger and drive Alzheimer-like neuropathology in mice. J Neuroinflammation 9:151.

Krstic D, Knuesel I: Deciphering the mechanism underlying late-onset Alzheimer disease. Nat Rev Neurol 2013, 9:25-34.

Landrigan PJ, Sonawane B, Butler RN, Trasande L, Callan R, Droller D. 2005. Early environmental origins of neurodegenerative disease in later life. Environ Health Perspect 113(9): 1230-1233.

Lee J, Freeman JL. 2014. Zebrafish as a model for investigating developmental lead (Pb) neurotoxicity as a risk factor in adult neurodegenerative disease: a mini-review. Neurotoxicology 43: 57-64.

Lei X, Guo Q, Zhang J. 2012. Mechanistic insights into neurotoxicity induced by anesthetics in the developing brain. International journal of molecular sciences 13(6): 6772-6799.

Lichtenstein MP, Carriba P, Masgrau R, Pujol A, Galea E. 2010. Staging anti-inflammatory therapy in Alzheimer's disease. Frontiers in aging neuroscience 2: 142.

Liu, M.C., Liu, X.Q., Wang, W., Shen, X.F., Che, H.L., Guo, Y.Y., Zhao, M.G., Chen, J.Y., Luo, W.J., 2012. Involvement of microglia activation in the lead induced long-term potentiation impairment. PLoS One 7(8), e43924.

Lloret, A., Fuchsberger, T., Giraldo, E., Vina, J., 2015. Molecular mechanisms linking amyloid beta toxicity and Tau hyperphosphorylation in Alzheimers disease. Free Radic Biol Med 83, 186-191.

Monnet-Tschudi F, Zurich MG, Honegger P. 2007. Neurotoxicant-induced inflammatory response in three-dimensional brain cell cultures. Hum Exp Toxicol 26(4): 339-346.

Mutter, J., Naumann, J., Sadaghiani, C., Schneider, R., Walach, H., 2004. Alzheimer disease: mercury as pathogenetic factor and apolipoprotein E as a moderator. Neuro Endocrinol Lett 25(5), 331-339.

Nakajima K, Kohsaka S. 2004. Microglia: Neuroprotective and neurotrophic cells in the central nervous system. Current Drug Targets-Cardiovasc & Haematol Disorders 4: 65-84.

Niranjan R. 2014. The role of inflammatory and oxidative stress mechanisms in the pathogenesis of Parkinson's disease: focus on astrocytes. Mol Neurobiol 49(1): 28-38.

Olmos-Alonso, A., Schetters, S.T., Sri, S., Askew, K., Mancuso, R., Vargas-Caballero, M., Holscher, C., Perry, V.H., Gomez-Nicola, D., 2016. Pharmacological targeting of CSF1R inhibits microglial proliferation and prevents the progression of Alzheimer's-like pathology. Brain 139(Pt 3), 891-907.

Omelchenko IA, Nelson CS, Allen CN. 1997. Lead inhibition of N-methyl-D-aspartate receptors containing NR2A, NR2C and NR2D subunits. J Pharmacol Exp Ther 282(3): 1458-1464.

Peng, S., Wuu, J., Mufson, E.J., Fahnestock, M. 2005. Precursor form of brain-derived neurotrophic factor and mature brain-derived neurotrophic factor are decreased in the pre-clinical stages of Alzheimer's disease. J Neurochem 93(6), 1412-1421.

Poo MM. (2001) Neurotrophins as synaptic modulators. Nat Rev Neurosci. 2: 24–32.

Sandström von Tobel, J., D. Zoia, et al. (2014). "Immediate and delayed effects of subchronic Paraquat exposure during an early differentiation stage in 3D-rat brain cell cultures." Toxicol Lett. DOI : 10.1016/j.toxlet.2014.02.001

Sandstrom J, Eggermann E, Charvet I, Roux A, Toni N, Greggio C, et al. 2017. Development and characterization of a human embryonic stem cell-derived 3D neural tissue model for neurotoxicity testing. Toxicol *In Vitro* 38: 124-135.

Schneider JS, Kidd SK, Anderson DW. 2013. Influence of developmental lead exposure on expression of DNA methyltransferases and methyl cytosine-binding proteins in hippocampus. Toxicol Lett 217(1): 75-81.

Schoemaker D, Gauthier S, Pruessner JC. 2014. Recollection and familiarity in aging individuals with mild cognitive impairment and Alzheimer's disease: a literature review. Neuropsychology review 24(3): 313-331.

Schwartz BS, Stewart WF, Bolla KI, Simon PD, Bandeen-Roche K, Gordon PB, et al. 2000. Past adult lead exposure is associated with longitudinal decline in cognitive function. Neurology 55(8): 1144-1150.

Schwartz MP, Hou Z, Propson NE, Zhang J, Engstrom CJ, Santos Costa V, et al. 2015. Human pluripotent stem cell-derived neural constructs for predicting neural toxicity. Proc Natl Acad Sci U S A 112(40): 12516-12521.

Sherer, T.B., Betarbet, R., Greenamyre, J.T., 2002. Environment, mitochondria, and Parkinson's disease. Neuroscientist 8(3), 192-197.

Silva AJ, Paylor R, Wehner JM, Tonegawa S. 1992. Impaired spatial learning in alpha-calcium-calmodulin kinase II mutant mice. Science 257: 206-211.

Steece-Collier, K., Maries, E., Kordower, J.H., 2002. Etiology of Parkinson's disease: Genetics and environment revisited. Proc Natl Acad Sci U S A 99(22), 13972-13974.

Stewart WF, Schwartz BS, Davatzikos C, Shen D, Liu D, Wu X, et al. 2006. Past adult lead exposure is linked to neurodegeneration measured by brain MRI. Neurology 66(10): 1476-1484.

Tansey MG, Goldberg MS. 2009. Neuroinflammation in Parkinson's disease: Its role in neuronal death and implications for therapeutic intervention. Neurobiol Dis.

Tartaglione, A.M., Venerosi, A., Calamandrei, G., 2016. Early-Life Toxic Insults and Onset of Sporadic Neurodegenerative Diseases-an Overview of Experimental Studies. Curr Top Behav Neurosci 29, 231-264.

Tsang, F., Soong, T.W., 2003. Interactions between environmental and genetic factors in the pathophysiology of Parkinson's disease. IUBMB Life 55(6), 323-327.

Verkhratsky A, Parpura V, Pekna M, Pekny M, Sofroniew M. 2014. Glia in the pathogenesis of neurodegenerative diseases. Biochemical Society Transactions 42(5): 1291-1301.

Walters JL, Paule MG. 2017. Review of preclinical studies on pediatric general anesthesia-induced developmental neurotoxicity. Neurotoxicol Teratol 60: 2-23.

Wayman GA, Lee YS, Tokomitsu H, Silva A, Soderling TR. (2008) Calmodulin-kinases: modulators of neuronal development and plasticity. Neuron 59: 914-931.

Whitton PS. 2007. Inflammation as a causative factor in the aetiology of Parkinson's disease. Br J Pharmacol 150(8): 963-976.

Xiao Y, Fu H, Han X, Hu X, Gu H, Chen Y, et al. 2014. Role of synaptic structural plasticity in impairments of spatial learning and memory induced by developmental lead exposure in Wistar rats. PLoS One 9(12): e115556.

Zawia NH, Basha MR. 2005. Environmental risk factors and the developmental basis for Alzheimer's disease. Rev Neurosci 16(4): 325

Zurich M-G, Eskes C, Honegger P, Bérode M, Monnet-Tschudi F. 2002. Maturation-dependent neurotoxicity of lead aceate *in vitro*: Implication of glial reactions. J Neurosc Res 70: 108-116.

Appendix 1: List of MIE(s), KE(s) and AO(s) in the AOP

List of MIE(s) in the AOP

Event: 201: Binding of antagonist, NMDA receptors

Short Name: Binding of antagonist, NMDA receptors

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:13 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	MolecularInitiatingEvent
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	MolecularInitiatingEvent

Stressors

Name
Lead

Biological Context

Level of Biological Organization
Molecular

Cell term

Cell term
neuron

Evidence for Perturbation by Stressor

Overview for Molecular Initiating Event

Glu and glycine are endogenous agonists that bind to LBD of specific NMDA receptor subunits. In this binding site numerous competitive exogenous antagonists have been identified to cause closure of binding site and inhibition of NMDA receptor (reviewed in

Traynelis et al., 2010). Here, are listed some known competitive antagonists for NMDA receptor, some of them are specific to NR1 subunit and some to NR2 subunit:

α-AA, α-aminoadipate;

5,7-DCKA, 5,7-dichlorokynurenic acid;

7-CKA, 7-chlorokynurenic acid;

ACEA-1011, 5-chloro-7-trifluoromethyl-1,4-dihydro-2,3-quinoxalinedione;

ACEA-1021, licostinel;

AP5, 2-amino-5-phosphonopentanoate;

AP7, 2-amino-7-phosphonopentanoate;

CGP-61594,(±)-trans-4-[2-(4-azidophyenyl)acetylamino]-5,7-dichloro-1,2,3,4-tetrahydroquinoline-2-carboxylic acid;

CGP-40116, d-(E)-2-amino-4-methyl-5-phosphono-3-pentenoic acid;

CGP-43487, d-(E)-2-amino-4-methyl-5-phosphono-3-pentenoic acid methyl ester;

CGP-58411, 7-chloro-4-hydroxy-3-phenyl-1H-quinolin-2-one;

CGS-19755, (2R,4S)-4-(phosphonomethyl)piperidine-2-carboxylic acid;

CPP, 4-(3-phosphonopropyl) pizerazine-2-carboxylic acid;

GV150,526A, gavestinel;

GV196,771A,(E)-4,6-dichloro-3-[(2-oxo-1-phenyl-3-pyrrolidinylidene)methyl]-1H-indole-2-carboxylic acid;

L-689,560,4-trans-2-carboxy-5,7-dichloro-4-phenylaminocarbonylamino-1,2,3,4-tetrahydroquinoline;

L-701,324, 7-chloro-4-hydroxy-3-(3-phenoxy)phenyl-2(1H)-quinolone;

MDL105,519,(E)-3-(2-phenyl-2-carboxyethenyl)-4, 6-dichloro-1H-indole-2-carboxylic acid;

PBPD, (2S,3R)-1-(biphenyl-4-carbonyl)piperazine-2,3-dicarboxylic acid;

PMPA, (R,S)-4-(phosphonomethyl)-piperazine-2-carboxylic acid;

PPDA, (2S,3R)-1-(phenanthren-2-carbonyl)piperazine-2,3-dicarboxylic acid

Besides competitive antagonists, noncompetitive antagonists have also been designed like phenylethanolamine ifenprodil that interacts with the NR2B extracellular amino-terminal domain. It has been suggested that they act by stabilizing an agonist-bound state in which the receptor has a low open probability. Other more potent derivatives of ifenprodil are: α-(4-hydroxyphenyl)-β-methyl-4-(phenylmethyl)-1-piperidine propanol (Ro 25-6981), 1-[2-(4-hydroxy-phenoxy)-ethyl]-4-(4-methyl-benzyl)-piperidin-4-ol (Ro 63-1908), besonprodil (CI-1041), and traxoprodil mesylate (CP-101,606). Ethanol has been proposed to be a noncompetitive antagonist of NMDA receptors, binding to NR2 subunit (Nagy, 2008). Inhibition of NMDA receptor function by ethanol and interactions between ethanol and the noncompetitive NMDA receptor antagonist ifenprodil have been examined in neocortical neurons from rat and human embryonic kidney (HEK) 293 cells expressing recombinant NMDA receptors (Lovinger, 1995). Recently, a structural model has been suggested that predicts the presence of four sites of ethanol action on the NMDA receptor,

each containing four pairs of positions in the NR1/NR2 subunits (reviewed in Chandrasekar, 2013). Some other antagonists can become trapped in the pore of the NMDA receptor after channel closure and these antagonists are called uncompetitive or trapping blockers. The most well studied NMDA receptor uncompetitive antagonists are Mg2+, polyamines, phencyclidine, ketamine, MK-801, memantine, amantadine, pentamidine, 9-tetrahydroaminoacridine, dextromethorphan, and its metabolite dextrorphan. MK-801 has been shown to prevent toluene-induced alterations in pattern-elicited visual-evoked potentials *in vivo*, suggesting the possibility that the binding site of toluene might be common with the one of MK-801 (Bale et al., 2007). However, another study suggests that toluene interference with the NMDA receptor might not be exclusively because of the binding to the channel pore (Smothers and Woodward, 2007) but it may involve some other binding sites. Lead (Pb2+) is considered a voltage independent antagonist of NMDA receptors and it is believed that possibly shares the same binding site with Zn2+ (reviewed in Neal and Guilarte, 2010; Traynelis et al., 2010). However, studies done in recombinant NR2A- and NR2B- containing NMDA receptors with mutated Zn2+ binding sites exhibit that additional structural elements, different from those important for Zn2+ binding are involved in Pb2+ binding site (reviewed in Neal and Guilarte, 2010). Similarly, there are contradicting experimental evidence and disagreement about Pb2+'s role as competitive or non-competitive antagonist (Neal and Guilarte, 2010). Pb2+ -induced inhibition of NMDAR during synaptogenesis in hippocampal neurons altered synaptic NMDAR composition, resulting in a decrease in NR2A-containing NMDARs at the established synapses (Neal et al., 2011).

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

The evolution of NMDAR subunits (NR1, NR2, NR3) is well-conserved throughout different species from lower organism to mammals, including humans (Ewald and Cline, 2009; Tikhonov and Magazanik, 2009; Koo and Hampson, 2010; Teng et al., 2010; Flores-soto et al., 2012).

Many of the binding sites for the noncompetitive or competitive antagonists e.g. for binding of dizocilpine (MK-801), phencyclidine, D-2-amino-5-phosphonopentanoate (AP5) and 3-((R)-2-carboxypiperazin-4-yl)-propyl-1-phosphonic acid (R-CPP) are also conserved in Drosophila (reviewed in Xia and Chiang, 2009).

Cellular membranes can be prepared from different brain areas of distinct species. Using [3H]MK-801, high affinity binding sites for MK-801 were detected in membranes of the rat brain (Woodruff et al., 1987). The same binding assay has been used in preparations from human brains mostly from brain of patients with neurodegenerative disorders (Slater et al., 1993) as well as from brain of different marine, avian species (Scheuhammer et al., 2008) and insects (Eldefrawi et al., 1993).

Key Event Description

Biological state: L-glutamate (Glu) is a neurotransmitter with important role in the regulation of brain development and maturation processes. Two major classes of Glu receptors, ionotropic and metabotropic, have been identified. Due to its physiological and pharmacological properties, Glu activates three classes of ionotropic receptors named: α-amino-3-hydroxy-5-methyl-4-isoazolepropionic acid (AMPA receptors), 2-carboxy-3-carboxymethyl-4-isopropenylpyrrolidine (kainate receptors) and N-methyl-D-aspartate (NMDA receptors, NMDARs), which transduce the postsynaptic signal. Ionotropic glutamate receptors are integral membrane proteins formed by four large subunits that compose a central ion channel pore. In case of NMDA receptors, two NR1 subunits are combined with either two NR2 (NR2A, NR2B, NR2C, NR2D) subunits and less commonly are assembled together with a combination of NR2 and NR3 (A, B) subunits (reviewed in Traynelis et al., 2010). To be activated NMDA receptors require simultaneous binding of both glutamate to NR2 subunits and of glycine to either NR1 or NR3 subunits that provide the specific binding sites named extracellular ligand-binding domains (LBDs). Apart from LBDs, NMDA receptor subunits contain three more domains that are considered semiautonomous: 1) the extracellular amino-terminal domain that plays important role in assembly and trafficking of these receptors; 2) the transmembrane domain that is linked with LBD and contributes to the formation of the core of the ion channel and 3) the intracellular carboxyl-terminal domain that influences membrane targeting, stabilization, degradation and post-translation modifications.

Biological compartments: The genes of the NMDAR subunits are expressed in various tissues and are not only restricted to the nervous system. The level of expression of these receptors in neuronal and non-neuronal cells depends on: transcription, chromatin remodelling, mRNA levels, translation, stabilization of the protein, receptor assembly and trafficking, energy metabolism and numerous environmental stimuli (reviewed in Traynelis et al., 2010).

In hippocampus region of the brain, NR2A and NR2B are the most abundant NR2 family subunits. NR2A-containing NMDARs are mostly expressed synaptically, while NR2B-containing NMDARs are found both synaptically and extrasynaptically (Tovar and Westbrook, 1999).

General role in biology: NMDA receptors, when compared to the other Glu receptors, are characterized by higher affinity for Glu, slower activation and desensitisation kinetics, higher permeability for calcium (Ca^{2+}) and susceptibility to potential-dependent blockage by magnesium ions (Mg^{2+}). NMDA receptors are involved in fast excitatory synaptic transmission and neuronal plasticity in the central nervous system (CNS). Functions of NMDA receptors:

1. They are involved in cell signalling events converting environmental stimuli to genetic changes by regulating gene transcription and epigenetic modifications in neuronal cells (Cohen and Greenberg, 2008).

2. In NMDA receptors, the ion channel is blocked by extracellular Mg^{2+} and Zn^{2+} ions, allowing the flow of Na^{+} and Ca^{2+} ions into the cell and K^{+} out of the cell which is voltage-dependent. Ca^{2+} flux through the NMDA receptor is considered to play a critical role in pre- and post-synaptic plasticity, a cellular mechanism important for learning and memory (Barria and Malinow, 2002).

3. The NMDA receptors have been shown to play an essential role in the strengthening of synapses and neuronal differentiation, through long-term potentiation (LTP), and the

weakening of synapses, through long-term depression (LTD). All these processes are implicated in the memory and learning function (Barria and Malinow, 2002).

How it is Measured or Detected

There is no OECD advised method for measuring NMDA receptor binding of antagonists. However, there are methods described in the scientific literature that allow measuring:

1. Ex vivo: The most common assay used is the NMDA receptor (MK801 site) radioligand competition binding assays (Reynolds, 2001; Gao et al., 2013; http://pdsp.med.unc.edu/UNC-CH%20Protocol%20Book.pdf; http://www.currentprotocols.com/WileyCDA/CPUnit/refId-ph0120.html). This assay is based on the use of the most potent and specific antagonist of this receptor, MK801 that is used to detect and differentiate agonists and antagonists (competitive and non-competitive) that bind to this specific site of the receptor. Also radioligand competition binding assay can be performed using D, L-(E)-2-amino-4-[3H]-propyl-5-phosphono-3-pentenoic acid ([3H]-CGP 39653), a high affinity selective antagonist at the glutamate site of NMDA receptor, which is a quantitative autoradiography technique (Mugnaini et al., 1996). D-AP5, a selective N-methyl-D-aspartate (NMDA) receptor antagonist that competitively inhibits the glutamate binding site of NMDA receptors, can be studied by evoked electrical activity measurements. AP5 has been widely used to study the activity of NMDA receptors particularly with regard to researching synaptic plasticity, learning, and memory (Evans et al.,1982; Morris, 1989).

2. In silico: The prediction of NMDA receptor targeting is achievable by combining database mining, molecular docking, structure-based pharmacophore searching, and chemical similarity searching methods together (Korkut and Varnali, 2003; Koutsoukos et al., 2011; Gao et al., 2013; Mazumder and Borah, 2014; Chtitaa et al., 2015).

References

Bale AS, Jackson MD, Krantz QT, Benignus VA, Bushnell PJ, Shafer TJ, Boyes WK. (2007) Evaluating the NMDA-glutamate receptor as a site of action for toluene, *in vivo*. Toxicol Sci. 98: 159-66.

Barria A, Malinow R. (2002) Subunit-specific NMDA receptor trafficking to synapses. Neuron 35: 345-353.

Chandrasekar R. (2013) Alcohol and NMDA receptor: current research and future direction. Front Mol Neurosci. 6: 14.

Chtitaa S, Larifb M, Ghamalia M, Bouachrinec M, Lakhlifia T. (2015) DFT-based QSAR Studies of MK801 derivatives for non competitive antagonists of NMDA using electronic and topological descriptors. Journal of Taibah University for Science. 9: 143-154.

Cohen S, Greenberg ME. (2008) Communication between the synapse and the nucleus in neuronal development, plasticity, and disease. Ann Rev Cell Dev Biol 24: 183-209.

Eldefrawi ME, Anis NA, Eldefrawi AT. (1993) Glutamate receptor inhibitors as potential insecticides. Arch Insect Biochem Physiol. 22: 25-39.

Evans RH, Francis AA, Jones AW, Smith DA, Watkins JC. (1982) The Effects of a Series of ω-Phosphonic α-Carboxylic Amino Acids on Electrically Evoked and Excitant Amino Acid-Induced Responses in Isolated Spinal Cord Preparations. Br J Pharmac. 75: 65-75.

Ewald RC, Cline HT. (2009) Cloning and phylogentic analysis of NMDA receptor subunits NR1, NR2A and NR2B in Xenopus laevis tadpoles. Front Mol Neurosci. 2: 4.

Flores-soto ME, Chaparro-Huerta V, Escoto-Delgadillo M, Vazuez-Valls E, Gonzalez-Castaneda RE, Beas-Zarate C. (2012) Structure and function of NMDA-type glutamate receptor subunits. Neurologia 27: 301-310.

Gao L, Fang JS, Bai XY, Zhou D, Wang YT, Liu AL, Du GH. (2013) In silico Target Fishing for the Potential Targets and Molecular Mechanisms of Baicalein as an Antiparkinsonian Agent: Discovery of the Protective Effects on NMDA Receptor-Mediated Neurotoxicity. Chem Biol Drug Des. 81: 675-87.

Koo JCP, Hampson DR. (2010) Phylogenic and evolutionary analysis of glutamate receptor based on extant invertebrate genes. JULS 1: 42-48.

Korkut A, Varnali T. (2003) Quantitative structure activity relationship (QSAR) of competitive N-methyl-D-aspartate (NMDA) antagonists. Mol Phys 101: 3285-3291.

Koutsoukas A, Simms B, Kirchmair J, Bond PJ, Whitmore AV, Zimmer S, Young MP, Jenkins JL, Glick M, Glen RC, Bender A. (2011) From in silico target prediction to multi-target drug design: current databases, methods and applications. J Proteomics 74: 2554-2574.

Lovinger DM. (1995) Developmental decrease in ethanol inhibition of N-methyl-D-aspartate receptors in rat neocortical neurons: relation to the actions of ifenprodil. J Pharmacol Exp Ther. 274: 164-172.

Mazumder MK, Borah A. (2014) Piroxicam inhibits NMDA receptor-mediated excitotoxicity through allosteric inhibition of the GluN2B subunit: An in silico study elucidating a novel mechanism of action of the drug. Medical Hypotheses 83: 740–746.

Morris RJ. (1989) Synaptic Plasticity and Learning: Selective Impairment of Learning in Rats and Blockade of Long-Term Potentiation *in vivo* by the N-Methyl-D-Aspartate Receptor Antagonist AP5. J Neurosci 9: 3040-3057.

Mugnaini M, van Amsterdam FT, Ratti E, Trist DG, Bowery NG. (1996) Regionally different N-methyl-D-aspartate receptors distinguished by ligand binding and quantitative autoradiography of [3H]-CGP 39653 in rat brain. Br J Pharmacol 119: 819–828.

Nagy J. (2008) Alcohol related changes in regulation of NMDA receptor functions. Curr Neuropharmacol 6: 39-54.

Neal AP, Guilarte TR. (2010) Molecular Neurobiology of Lead (Pb2+): Effects on Synaptic Function. Mol Neurobiol. 42: 151-160.

Neal AP. Worley PF. Guilarte TR (2011) Lead exposure during synaptogenesis alters NMDA receptor targeting via NMDA receptor inhibition. Neurotoxicology. 32:281-289.

Reynolds IJ. (2001) [3H](+)MK801 radioligand binding assay at the N-methyl-D-aspartate receptor. Curr Protoc Pharmacol. Chapter 1:Unit 1.20. doi: 10.1002/0471141755.ph0120s11.

Scheuhammer AM, Basu N, Burgess NM, Elliott JE, Campbell GD, Wayland M, Champoux L, Rodrigue J. (2008) Relationships among mercury, selenium, and

neurochemical parameters in common loons (Gavia immer) and bald eagles (Haliaeetus leucocephalus). Ecotoxicology 17: 93-101.

Slater P, McConnell SE, D'Souza SW, Barson AJ. (1993) Postnatal changes in N-methyl-D-aspartate receptor binding and stimulation by glutamate and glycine of [3H]-MK-801 binding in human temporal cortex. Br J Pharmacol. 108: 1143-1149.

Smothers CT, Woodward JJ. (2007) Pharmacological characterization of glycine-activated currents in HEK 293 cells expressing N-methyl-d-aspartate NR1 and NR3 subunits. J Pharmacol Exp Ther. 322: 739-748.

Teng H, Cai W, Zhou L, Zhang J, Liu Q, Wang Y, et al. (2010) Evolutionary mode of functional divergence of vertebrate NMDA receptor subunit 2 Genes. PLoS ONE. 5(10): e13342.

Tikhonov DB, Magazanik LG. (2009) Origin and molecular evolution of ionotropic glutamate receptors. Neurosci Behav Physiol. 39: 763-772.

Tovar KR, Westbrook GL. (1999) The incorporation of NMDA receptors with a distinct subunit composition at nascent hippocampal synapses *in vitro*. J Neurosci. 19: 4180–4188.

Traynelis S, Wollmuth LP, McBain CJ, Menniti FS, Vance KM, Ogden KK, Hansen KB, Yuan H, Myers SJ, Dingledine R. (2010) Glutamate receptor ion channels: structure, regulation, and function. Pharmacol Rev. 62: 405-496.

Woodruff GN, Foster AC, Gill R, Kemp JA, Wong EH, Iversen LL. (1987) The interaction between MK-801 and receptors for N-methyl-D-aspartate: functional consequences. Neuropharmacology 26(7B): 903-909.

Xia S, Chiang AS. (2009) NMDA Receptors in Drosophila. In: Van Dongen AM, editor. Biology of the NMDA Receptor. Boca Raton (FL): CRC Press; Chapter 10. Available from: http://www.ncbi.nlm.nih.gov/books/NBK5286/

List of KE(s) in the AOP

Event: 195: Inhibition, NMDARs

Short Name: Inhibition, NMDARs

Key Event Component

Process	Object	Action
NMDA glutamate receptor activity	NMDA selective glutamate receptor complex	decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	KeyEvent
Aop:13 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	KeyEvent

Biological Context

Level of Biological Organization
Molecular

Cell term

Cell term
neuron

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

The cellular expression of the NMDAR subunits has been studied in both adult human cortex and hippocampus (Scherzer et al., 1998) as well as during the development of the human hippocampal formation (Law et al., 2003). The whole-cell patch clamp recording techniques have been used in NMDA receptors expressed in human TsA cells (derivative of the human embryonic kidney cell line HEK-293) (Ludolph et al., 2010). Cell-attached single-channel recordings of NMDA channels has been carried out in human dentate gyrus

granule cells acutely dissociated from slices prepared from hippocampi surgically removed from human patients (Lieberman and Mody, 1999).

It is important to note that in invertebrates the glutamatergic synaptic transmission has inhibitory and not excitatory role like in vertebrates. This type of neurotransmission is mediated by glutamate-gated chloride channels that are members of the 'cys-loop' ligand-gated anion channel superfamily found only in invertebrates. The subunits of glutamate-activated chloride channel have been isolated from C. elegans and from Drosophila (Blanke and VanDongen, 2009).

Key Event Description

Biological state: L-glutamate (Glu) is a neurotransmitter with important role in the regulation of brain development and maturation processes. Two major classes of Glu receptors, ionotropic and metabotropic, have been identified. Due to its physiological and pharmacological properties, Glu activates three classes of ionotropic receptors named: α-amino-3-hydroxy-5-methyl-4-isoazolepropionic acid (AMPA receptors), 2-carboxy-3-carboxymethyl-4-isopropenylpyrrolidine (kainate receptors) and N-methyl-D-aspartate (NMDA receptors, NMDARs), which transduce the postsynaptic signal. Ionotropic glutamate receptors are integral membrane proteins formed by four large subunits that compose a central ion channel pore. In case of NMDA receptors, two NR1 subunits are combined with either two NR2 (NR2A, NR2B, NR2C, NR2D) subunits and less commonly are assembled together with a combination of NR2 and NR3 (A, B) subunits (reviewed in Traynelis et al., 2010). To be activated NMDA receptors require simultaneous binding of both glutamate to NR2 subunits and of glycine to either NR1 or NR3 subunits that provide the specific binding sites named extracellular ligand-binding domains (LBDs). Apart from LBDs, NMDA receptor subunits contain three more domains that are considered semiautonomous: 1) the extracellular amino-terminal domain that plays important role in assembly and trafficking of these receptors; 2) the transmembrane domain that is linked with LBD and contributes to the formation of the core of the ion channel and 3) the intracellular carboxyl-terminal domain that influences membrane targeting, stabilization, degradation and post-translation modifications.

Biological compartments: The genes of the NMDAR subunits are expressed in various tissues and are not only restricted to the nervous system. The level of expression of these receptors in neuronal and non-neuronal cells depends on: transcription, chromatin remodelling, mRNA levels, translation, stabilization of the protein, receptor assembly and trafficking, energy metabolism and numerous environmental stimuli (reviewed in Traynelis et al., 2010).

In hippocampus region of the brain, NR2A and NR2B are the most abundant NR2 family subunits. NR2A-containing NMDARs are mostly expressed synaptically, while NR2B-containing NMDARs are found both synaptically and extrasynaptically (Tovar and Westbrook, 1999).

General role in biology: NMDA receptors, when compared to the other Glu receptors, are characterized by higher affinity for Glu, slower activation and desensitisation kinetics, higher permeability for calcium (Ca2+) and susceptibility to potential-dependent blockage by magnesium ions (Mg2+). NMDA receptors are involved in fast excitatory synaptic transmission and neuronal plasticity in the central nervous system (CNS). Functions of NMDA receptors:

1. They are involved in cell signalling events converting environmental stimuli to genetic changes by regulating gene transcription and epigenetic modifications in neuronal cells (Cohen and Greenberg, 2008).

2. In NMDA receptors, the ion channel is blocked by extracellular Mg2+ and Zn2+ ions, allowing the flow of Na+ and Ca2+ ions into the cell and K+ out of the cell which is voltage-dependent. Ca2+ flux through the NMDA receptor is considered to play a critical role in pre- and post-synaptic plasticity, a cellular mechanism important for learning and memory (Barria and Malinow, 2002).

3. The NMDA receptors have been shown to play an essential role in the strengthening of synapses and neuronal differentiation, through long-term potentiation (LTP), and the weakening of synapses, through long-term depression (LTD). All these processes are implicated in the memory and learning function (Barria and Malinow, 2002).

How it is Measured or Detected

No OECD methods are available to measure the activation state of NMDA receptors.

The measurement of the activation or the inhibition of NMDA receptors is done indirectly by recording the individual ion channels that are selective to Na+, K+ and Ca+2 by the patch clamp technique. This method relies on lack of measurable ion flux when NMDA ion channel is closed, whereas constant channel specific conductance is recorded at the open state of the receptor (Blanke and VanDongen, 2009). Furthermore, this method is based on the prediction that activation or inhibition of an ion channel results from an increase in the probability of being in the open or close state, respectively.

The whole-cell patch clamp recording techniques have also been used to study synaptically-evoked NMDA receptor-mediated excitatory or inhibitory postsynaptic currents (EPSCs and IPSCs, respectively) in brain slices and neuronal cells, allowing the evaluation of the activated or inhibited state of the receptor (Ogdon and Stanfield, 2009; Zhao et al., 2009).

Microelectrode array (MEA) recordings are used to measure electrical activity in cultured neurons in response to NMDA receptor activation or inactivation (Keefer et al., 2001, Gramowski et al., 2000 and Gopal, 2003; Johnstone et al., 2010). MEAs can also be applied in higher throughput platforms to facilitate screening of numerous chemical compounds based on electrical activity measurements (McConnell et al., 2012).

References

Barria A, Malinow R. (2002) Subunit-specific NMDA receptor trafficking to synapses. Neuron 35: 345-353.

Blanke ML, VanDongen AMJ. (2009) Activation Mechanisms of the NMDA Receptor. In: Van Dongen AM, editor. Biology of the NMDA Receptor. Boca Raton (FL): CRC Press; Chapter 13. Available from: http://www.ncbi.nlm.nih.gov/books/NBK5274/

Cohen S, Greenberg ME. (2008) Communication between the synapse and the nucleus in neuronal development, plasticity, and disease. Ann Rev Cell Dev Biol 24: 183-209.

Gopal K. (2003) Neurotoxic effects of mercury on auditory cortex networks growing on microelectrode arrays: a preliminary analysis. Neurotoxicol Teratol. 25: 69-76.

Gramowski A, Schiffmann D, Gross GW. (2000) Quantification of acute neurotoxic effects of trimethyltin using neuronal networks cultures on microelectrode arrays. Neurotoxicology 21: 331-342.

Johnstone AFM, Gross GW, Weiss D, Schroeder O, Shafer TJ. (2010). Use of microelectrode arrays for neurotoxicity testing in the 21st century Neurotoxicology 31: 331-350.

Keefer E, Norton S, Boyle N, Talesa V, Gross G. (2001) Acute toxicity screening of novel AChE inhibitors using neuronal networks on microelectrode arrays. Neurotoxicology 22: 3-12.

Law AJ, Weickert CS, Webster MJ, Herman MM, Kleinman JE, Harrison PJ. (2003) Expression of NMDA receptor NR1, NR2A and NR2B subunit mRNAs during development of the human hippocampal formation. Eur J Neurosci. 18: 1197-1205.

Lieberman DN, Mody I. (1999) Properties of single NMDA receptor channels in human dentate gyrus granule cells. J Physiol. 518: 55-70.

Ludolph AG, Udvardi PT, Schaz U, Henes C, Adolph O, Weigt HU, Fegert JM, Boeckers TM, Föhr KJ. (2010) Atomoxetine acts as an NMDA receptor blocker in clinically relevant concentrations. Br J Pharmacol. 160: 283-291.

McConnell ER, McClain MA, Ross J, LeFew WR, Shafer TJ (2012). Evaluation of multi-well microelectrode arrays for neurotoxicity screening using a chemical training set Neurotoxicology 33: 1048-1057.

Ogdon D, Stanfield P. (2009) Patch clamp techniques for single channel and whole-cell recording. Chapter 4, pages 53-78. http://www.utdallas.edu/~tres/microelectrode/microelectrodes_ch04.pdf

Scherzer CR, Landwehrmeyer GB, Kerner JA, Counihan TJ, Kosinski CM, Standaert DG, Daggett LP, Veliçelebi G, Penney JB, Young AB. (1998) Expression of N-methyl-D-aspartate receptor subunit mRNAs in the human brain: hippocampus and cortex. J Comp Neurol. 390: 75-90.

Tovar KR, Westbrook GL. (1999) The incorporation of NMDA receptors with a distinct subunit composition at nascent hippocampal synapses *in vitro*. J Neurosci. 19: 4180–4188.

Traynelis S, Wollmuth LP, McBain CJ, Menniti FS, Vance KM, Ogden KK, Hansen KB, Yuan H, Myers SJ, Dingledine R. (2010) Glutamate receptor ion channels: structure, regulation, and function. Pharmacol Rev. 62: 405-496.

Zhao Y, Inayat S, Dikin DA, Singer JH, Ruoff RS, Troy JB. (2009) Patch clamp technique: review of the current state of the art and potential contributions from Nanoengineering. Proc. IMechE 222, Part N: J. Nanoengineering and Nanosystems 149. DOI: 10.1243/17403499JNN149.

Event: 52: Decreased, Calcium influx

Short Name: Decreased, Calcium influx

Key Event Component

Process	Object	Action
calcium ion transport	calcium ion	decreased

Biological Context

Level of Biological Organization
Cellular

Cell term

Cell term
neuron

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
mice	Mus sp.	High	NCBI
zebrafish	Danio rerio	High	NCBI

Ca2+ homeostatic system is known to be highly conserved throughout evolution and is present from humans to invertebrates (Case et al., 2007).

Key Event Description

Biological state: Under physiological resting conditions of the cell, the free intracellular Ca2+ reaches around 100 nM, whereas the extracellular Ca2+ can be found at higher concentrations of 1.2 mM that under certain stimulus may invade the cell (Berridge et al, 2000). Six to seven oxygen atoms surround Ca2+, whereas the protein chelator of Ca2+ is the EF motif that is present in many proteins such as calmodulin (Clapham, 2007). The EF-hand is a helix-loop-helix calcium-binding motif in which two helices pack together at an angle of approximately 90 degrees (Lewit-Bentley and Réty, 2000). The two helices are separated by a loop region where calcium actually binds. The EF notation for the motif is

derived from the notation applied to the structure of parvalbumin, in which the E and F helices were originally identified as forming this calcium-binding motif.

Biological compartments: Ca2+ ions accumulate in the cytoplasm, cellular organelles (e.g. mitochondria and endoplasmic reticulum) and nucleus in response to diverse classes of stimuli.

General role in biology: In order to adapt to altered stimulus from exposure to different environmental factors, cells require signal transmission. However, signalling needs messengers whose concentration is modified upon stimulus (Clapham, 2007). Ca2+ ions act as an important intracellular messenger playing the role of ubiquitous signalling molecules and consequently regulate many different cellular functions (Berridge, 2012; Hagenston and Bading, 2011). Given its important role in processes that are fundamental to all cell types, Ca2+ homeostasis is tightly regulated by intracellular and extracellular mechanisms (Barhoumi et al., 2010). Intracellular Ca2+ concentration is regulated by opening or closing channels in the plasma membrane. Additionally, the Ca2+ ions can be released from intracellular stores of the endoplasmic reticulum (ER) through ryanodine receptors (RYRs) or inositol 1,4,5-trisphosphate receptors (InsP3Rs). Ca2+ homeostasis is also regulated by the mechanisms that remove Ca2+ from the cytosol, for example pumps in both cell membrane and ER membrane. In addition, cytosolic Ca2+ regulation involves accumulation of Ca2+ in mitochondria that have the capacity to buffer the excess of cytoplasmic Ca2+ ions. In neurons, Ca2+ ions regulate many critical functions. Firstly, they contribute to dendritic electrical signalling, producing postsynaptic depolarization by the current carried by Ca2+ ions. Secondly, Ca2+ activates Ca2+-sensitive proteins such as different kinases, calcineurin and calpain, triggering signalling pathways critical for cell physiology. Modification of the gene transcription is the final outcome of the Ca2+ ions impact on long-term modifications affecting neurotransmitters release (reviewed in Neher and Sakaba, 2008), neuronal differentiation, synapse function and cell viability (Clapham, 2007; Higley and Sabatini, 2012). Thus, the Ca2+ that enters and accumulates in cytoplasm and nucleus is a central signalling molecule that regulates synapse and neuronal cell function, including learning and memory processes (Berridge, 2012; Hagenston and Bading, 2011).

How it is Measured or Detected

No OECD method is available to measure intracellular Ca2+.

The gold standard method for measuring Ca2+ current through NMDA receptor is patch clamp electrophysiology (Blanke and VanDongen, 2009).

In vitro, well-established flow cytometric or high content imaging analysis with specific fluorescent dyes (Ca2+-sensitive fluorophores) such as Fura-2, Oregon Green-BAPTA, Fluo-4 and X-Rhod exist for determination of intracellular Ca2+ concentration. The use of different fluorometric calcium indicators in neuroscience and neurotoxicology have been recently reviewed by Grienberger and Konnerth (2012) and Calvo et al (2015).

Barhoumi et al. 2010 summarised all the methods to measure cytosolic Ca2+ alterations due to exposure to neurotoxic compounds, including steady state, short-term kinetic measurements of stimulated Ca2+ transients and dynamic measurements. This paper further discusses the strengths and weaknesses of each approach in intracellular Ca2+ measurements and its applicability in high throughput screening.

For quantitative estimation of Ca2+ in dendritic spines, besides of Ca2+-sensitive fluorophores the use of two-photon released caged neurotransmitters has been suggested as it allows direct stimulation of visualized spines (Higley and Sabatini, 2012). In Higley and Sabatini 2012 further technical information can be found in relation to study Ca2+ in dendritic spines.

Furthermore, there are three methods for measuring Ca2+ influx in NMDA receptors that involve the measurement of 1) relative Ca2+ permeability, 2) channel blockage by Ca2+, and 3) fractional Ca2+ currents from whole-cell currents determined in the presence of high concentrations of intracellular Fura-2 (Traynelis et al., 2010).

In vivo, two-photon Ca2+ imaging using Ca2+-sensitive fluorescent indicators that measure changes in intracellular Ca2+ concentration as a readout for suprathreshold and subthreshold neuronal activity has also been used to study learning and memory in live rodents (Chen et al., 2013) The last two decades the neuronal function of the larval and adult zebrafish has been extensively studied using Ca2+ imaging methods. By applying simple Ca2+ indicators such as dextran or acetoxymethyl esters to more powerful genetically encoded Ca2+ indicators, zebrafish provides a transparent model where live Ca2+ imaging can be successfully achieved (Kettunen, 2012).

Fluorescent Ca2+ indicators have been also used as Pb2+ sensors in order to resolve spatiotemporal changes in intracellular Pb2+ in relation to cellular signaling and intracellular divalent metal homeostasis (Vijveberg and Westerink, 2012).

Intra-cellular calcium concentration can be measured in cell cultures with the calcium sensitive fluorescent dye Fura-2 AM and fluorescence microscopy. This technique appeared to be more sensitive than the plate-reader based assay Meijer et al., 2014).

References

Barhoumi R, Qian Y, Burghardt RC, Tiffany-Castiglioni E. (2010) Image analysis of Ca2+ signals as a basis for neurotoxicity assays: promises and challenges. Neurotoxicol Teratol. 32: 16-24.

Berridge MJ, Lipp P, Bootman MD. (2000) The versatility and universality of calcium signalling. Nat Rev Mol Cell Biol. 1:11-21.

Berridge MJ. (2012) Calcium signalling remodelling and disease. Biochem Soc Trans. 40: 297-309.

Blanke ML, VanDongen AMJ. (2009) Activation Mechanisms of the NMDA Receptor. In: Van Dongen AM, editor. Biology of the NMDA Receptor. Boca Raton (FL): CRC Press; Chapter 13. Available from: http://www.ncbi.nlm.nih.gov/books/NBK5274/

Calvo M, Villalobos C, Núñez L. (2015) Calcium imaging in neuron cell death. Methods Mol Biol. 1254: 73-85.

Case RM, Eisner D, Gurney A, Jones O, Muallem S, Verkhratsky A. (2007) Evolution of calcium homeostasis: from birth of the first cell to an omnipresent signalling system. Cell Calcium 42: 345-350.

Chen JL, Andermann ML, Keck T, Xu NL, Ziv Y. (2013) Imaging neuronal populations in behaving rodents: paradigms for studying neural circuits underlying behavior in the mammalian cortex. J Neurosci. 33: 17631-17640.

Clapham DE. (2007) Calcium signaling. Cell 131: 1047-1058.

Grienberger C, Konnerth A. (2012) Imaging calcium in neurons. Neuron 73: 862-885.

Hagenston AM, Bading H. (2011) Calcium Signaling in Synapse-to-Nucleus Communication. Cold Spring Harb Perspect Biol. 3: a004564.

Higley MJ, Sabatini BL. (2012) Calcium signalling in dendritic spines. Cold Spring Harb Perspect Biol. 4: a005686.

Kettunen P. (2012) Calcium imaging in the zebrafish. Adv Exp Med Biol. 740: 1039-1071.

Lewit-Bentley A, Réty S. (2000) EF-hand calcium-binding proteins. Curr Opin Struct Biol. 2000 Dec;10(6):637-43.

Meijer M, Hendriks HS, Heusinkveld HJ, Langeveld WT, Westerink RH. 2014. Comparison of plate reader-based methods with fluorescence microscopy for measurements of intracellular calcium levels for the assessment of *in vitro* neurotoxicity. Neurotoxicology 45: 31-37.

Neher E., Sakaba T. (2008). Multiple roles of calcium ions in the regulation of neurotransmitter release. Neuron 59: 861-872.

Traynelis S, Wollmuth LP, McBain CJ, Menniti FS, Vance KM, Ogden KK, Hansen KB, Yuan H, Myers SJ, Dingledine R. (2010) Glutamate receptor ion channels: structure, regulation, and function. Pharmacol Rev. 62: 405-496.

Vijverberg HP, Westerink RH. 2012. Sense in Pb2+ sensing. Toxicol Sci 130(1): 1-3.

Event: 381: Reduced levels of BDNF

Short Name: BDNF, Reduced

Key Event Component

Process	Object	Action
gene expression	brain-derived neurotrophic factor	decreased
secretion	brain-derived neurotrophic factor	decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:13 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	KeyEvent
Aop:54 - Inhibition of Na+/I- symporter (NIS) leads to learning and memory impairment	KeyEvent
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	KeyEvent

Biological Context

Level of Biological Organization
Molecular

Cell term

Cell term
neural cell

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

Life Stage Applicability

Life Stage	Evidence
During brain development	High

Sex Applicability

Sex	Evidence
Mixed	High

BDNF plays a critical role in normal brain development in most vertebrates, primarily documented empirically in mammalian species. Klein et al. (2011) examined blood, serum, plasma and brain-tissue and measured BDNF levels in three different mammalian species: rat, pig, and mouse, using an ELISA method (Aid et al., 2007), whereas Trajkovska et al. 2007 determined BDNF levels in human blood.

There is compelling data that demonstrates the role of BDNF in brain development for many other taxa, including fish where it acts as neurotrophic factor in controlling cell proliferation (D'Angelo L et al., 2014; Heinrich and Pagtakhan, 2004) and birds where BDNF influences development of the brain area that involved in the song control (Brenowitz 2013) and the addition of new neurons to a cortical nucleus in adults . In the Xenopus visual system, BDNF acts as neurotrophic factor that mediates synaptic differentiation and maturation of the retinotectal circuit through cell autonomous TrkB signaling on retinal ganglion cells (Sanchez et al., 2006; Marshak et al., 2007).

Key Event Description

Biological state: BDNF belongs to a family of closely related neurotrophic factors named neurotrophins and is widely expressed in the developing and mature CNS. In the rodent cortex, postnatal BDNF expression is initially low but slowly increases to reach high levels around weaning. Therefore, BDNF expression peaks at a time when both structural and functional maturation of cortical circuitry occurs. During postnatal development, BDNF levels are dynamically regulated, in part by neuronal activity dependent mechanisms (Waterhouse and Xu, 2009). Glutamate has been shown to increase the transcription and release of BDNF. Indeed, BDNF is synthesized, stored and released from glutamatergic neurons (Lessmann et al., 2003).

Biological compartments: BDNF initially is synthesized as precursor proteins (proBDNF), which is processed intracellularly to be transformed in its mature form (mBDNF) after proteolytically cleaved in the synaptic cleft by plasmin which is a protease activated by tissue plasminogen activator (tPA) (Cohen-Cory et al., 2010). proBDNF is constantly secreted while tPA release and mBDNF production depends on neuronal excitation (Head et al., 2009). Storage and activity-dependent release of BDNF has been demonstrated in both dendrites and axon terminals (Waterhouse and Xu, 2009). More specifically, in hippocampus, BDNF appears to be stored in dendritic processes of neurons (Balkowiec and Katz, 2002). BDNF is abundant in cerebellum and cortex and has also been measured in cerebrospinal fluid (CSF) (Zhang et al., 2008), whole blood, plasma, serum (plasma without clotting factors) and platelets (Trajkovska et al., 2007). BDNF has been

found to be produced by astrocytes under both physiological and pathological conditions (Endo, 2005; Coco et al., 2013; Nelson and Alkon, 2014).

In humans (Pruunsild et al., 2007), mBDNF is sequestered in platelets, consequently BDNF can reach all tissues and organs. Lymphocytic cells have been shown to express BDNF *in vitro* similarly to eosinophils, dendritic cells, and endothelial cells. The visceral and airway epithelium are also significant sources of BDNF. Female reproductive system including ovaries, placenta and uterus also express BDNF (Wessels et al., 2014).

General role in biology: The biological functions of mBDNF are mediated by binding to tyrosine kinase B (TrkB) receptor that leads to the activation of three major intracellular signalling pathways, including MAPK, PI3K and PLCγ1 (Soulé et al., 2006). TrkB-mediated signaling regulates gene transcription in the nucleus through the activation of several transcription factors. These genes are involved in neurite outgrowth, synaptogenesis, synapse maturation and stabilization (Pang et al., 2004; Lu et al., 2005; Nelson and Alkon, 2014).

On the other hand, proBDNF binds to the p75 neurotrophin receptor (p75NTR) and activates RhoA, a small GTPase that regulates actin cytoskeleton polymerization leading to inhibition of axonal elongation, growth cone collapse, and apoptosis (Dubreuil et al., 2003; Yamauchi et al., 2004; Head et al., 2009).

How it is Measured or Detected

No OECD methods are available to measure BDNF protein and mRNA levels. Depending on the tissue or fluid measurements distinct methods are used.

Brain tissue: BDNF protein levels can be measured by commercial available antibody sandwich ELISA kits, Western blotting, immunohistochemistry and immunofluorescence. BDNF primers for different exons are available to determine mRNA levels by RT-PCR. The *Bdnf* gene consists of multiple alternative exons (ten in human, eight in rodents and six in lower vertebrates), and a single exon coding for the entire pro-BDNF protein (Cohen-Cory et al., 2010).

Cerebro-spinal fluid (CSF): There are available commercial antibody sandwich ELISA kits (Trajkovska et al., 2007) and immunobead-based multiplex assays for high throughput screening (Zhang et al., 2008).

Whole blood, serum, plasma and platelets: There are several commercial double antibody sandwich ELISA kits that can be used for identification of BDNF levels in biological fluids (Trajkovska et al., 2007).

Methodological considerations that have to be taken into account during sample preparation and measurement of BDNF by ELISA have been recently reviewed in Elfving et al. 2010. A study measuring BDNF by a commercially available ELISA kit in various tissues and biological liquids derived from distinct species revealed that BDNF is undetectable in mouse blood and pig plasma (Klein et al., 2011). This study also showed that in most cases BDNF levels are comparable to levels reported in humans and that there is positive correlation between blood BDNF levels and hippocampal BDNF levels in rats and pigs (Klein et al., 2011).

References

Aid T, Kazantseva A, Piirsoo M, Palm K, Timmusk T. (2007) Mouse and rat BDNF gene structure and expression revisited. J Neurosci Res. 85: 525-535.

Balkowiec A, Katz DM. (2002) Cellular mechanisms regulating activity-dependent release of native brain-derived neurotrophic factor from hippocampal neurons. J Neurosci. 22: 10399-10407.

Brenowitz EA. (2013) Testosterone and brain-derived neurotrophic factor interactions in the avian song control system. Neuroscience 239: 115-123.

Coco M, Caggia S, Musumeci G, Perciavalle V, Graziano AC, Pannuzzo G, Cardile V. (2013) Sodium L-lactate differently affects brain-derived neurothrophic factor, inducible nitric oxide synthase, and heat shock protein 70 kDa production in human astrocytes and SH-SY5Y cultures.J Neurosci Res. 91: 313-320.

Cohen-Cory S, Kidane AH, Shirkey NJ, Marshak S. (2010) Brain-derived neurotrophic factor and the development of structural neuronal connectivity. Dev Neurobiol. 70: 271-288.

D'Angelo L, De Girolamo P, Lucini C, Terzibasi ET, Baumgart M, Castaldo L, Cellerino A (2014). Brain-derived neurotrophic factor: mRNA expression and protein distribution in the brain of the teleost Nothobranchius furzeri. J Comp Neurol. 1;522(5):1004-30.

Dubreuil CI, Winton MJ, McKerracher L. (2003) Rho activation patterns after spinal cord injury and the role of activated Rho in apoptosis in the central nervous system. J Cell Biol. 162: 233-243.

Elfving B, Plougmann PH, Wegener G. (2010) Detection of brain-derived neurotrophic factor (BDNF) in rat blood and brain preparations using ELISA: pitfalls and solutions. J Neurosci Methods 187: 73-77.

Endo T. (2005) Glycans and glycan-binding proteins in brain: galectin-1-induced expression of neurotrophic factors in astrocytes. Curr Drug Targets. 6:427-436.

Head BP, Patel HH, Niesman IR, Drummond JC, Roth DM, Patel PM. (2009) Inhibition of p75 neurotrophin receptor attenuates isoflurane-mediated neuronal apoptosis in the neonatal central nervous system. Anesthesiology 110: 813-825.

Heinrich G, Pagtakhan CJ. (2004) Both 5' and 3' flanks regulate Zebrafish brain-derived neurotrophic factor gene expression. BMC Neurosci. 5: 19.

Klein AB, Williamson R, Santini MA, Clemmensen C, Ettrup A, Rios M, Knudsen GM, Aznar S. (2011) Blood BDNF concentrations reflect brain-tissue BDNF levels across species. Int J Neuropsychopharmacol. 14: 347-353.

Lessmann V, Gottmann K, Malcangio M. (2003) Neurotrophin secretion: current facts and future prospects. Prog Neurobiol. 69: 341-374.

Lu B, Pang PT, Woo NH. (2005) The yin and yang of neurotrophin action. Nat Rev Neurosci. 6: 603-614.

Marshak S, Nikolakopoulou AM, Dirks R, Martens GJ, Cohen-Cory S (2007)Cell-autonomous TrkB signaling in presynaptic retinal ganglion cells mediates axon arbor growth and synapse maturation during the establishment of retinotectal synaptic connectivity. J Neurosci 27:2444 –2456.

Nelson TJ, Alkon DL. (2014) Molecular regulation of synaptogenesis during associative learning and memory. Brain Res. pii: S0006-8993(14)01660-6. doi: 10.1016/j.brainres.2014.11.054.

Pang PT, Teng HK, Zaitsev E, Woo NT, Sakata K, Zhen S, Teng KK, Yung WH, Hempstead BL, Lu B. (2004) Cleavage of proBDNF by tPA/plasmin is essential for long-term hippocampal plasticity. Science. 306: 487-491.

Pruunsild P, Kazantseva A, Aid T, Palm K, Timmusk T. (2007) Dissecting the human BDNF locus: bidirectional transcription, complex splicing, and multiple promoters. Genomics. 90: 397-406.

Sanchez AL, Matthews BJ, Meynard MM, Hu B, Javed S, Cohen Cory S (2006) BDNF increases synapse density in dendrites of developing tectal neurons *in vivo*. Development 133:2477–2486.

Soulé J, Messaoudi E, Bramham CR. (2006) Brain-derived neurotrophic factor and control of synaptic consolidation in the adult brain. Biochem Soc Trans. 34 :600-604.

Trajkovska V, Marcussen AB, Vinberg M, Hartvig P, Aznar S, Knudsen GM. (2007) Measurements of brain-derived neurotrophic factor: methodological aspects and demographical data. Brain Res Bull. 73: 143-149.

Waterhouse EG, Xu B. (2009) New insights into the role of brain-derived neurotrophic factor in synaptic plasticity. Mol Cell Neurosci. 42: 81-89.

Wessels JM, Wu L, Leyland NA, Wang H, Foster WG. (2014) The Brain-Uterus Connection: Brain Derived Neurotrophic Factor (BDNF) and Its Receptor (Ntrk2) Are Conserved in the Mammalian Uterus. PLoS ONE 9: e94036.

Yamauchi J, Chan JR, Shooter EM. (2004) Neurotrophins regulate Schwann cell migration by activating divergent signaling pathways dependent on Rho GTPases. Proc Natl Acad Sci U S A. 101: 8774-8779.

Zhang J, Sokal I, Peskind ER, Quinn JF, Jankovic J, Kenney C, Chung KA, Millard SP, Nutt JG, Montine TJ. (2008) CSF multianalyte profile distinguishes Alzheimer and Parkinson diseases. Am J Clin Pathol. 129: 526-529.

Event: 55: N/A, Cell injury/death

Short Name: N/A, Cell injury/death

Key Event Component

Process	Object	Action
cell death		increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:48 - Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	KeyEvent
Aop:13 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	KeyEvent
Aop:38 - Protein Alkylation leading to Liver Fibrosis	KeyEvent
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	KeyEvent
Aop:144 - Lysosomal damage leading to liver inflammation	KeyEvent
Aop:17 - Binding of electrophilic chemicals to SH(thiol)-group of proteins and /or to seleno-proteins during brain development leads to impairment of learning and memory	KeyEvent

Biological Context

Level of Biological Organization
Cellular

Cell term

Cell term
eukaryotic cell

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
human and other cells in culture	human and other cells in culture	High	NCBI
Rattus norvegicus	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

Cell death is an universal event occurring in cells of any species[11].

Key Event Description

Two types of cell death can be distinguished by morphological features, although it is likely that these are two ends of a spectrum with possible intermediate forms. Apoptosis involves shrinkage, nuclear disassembly, and fragmentation of the cell into discrete bodies with intact plasma membranes. These are rapidly phagocytosed by neighbouring cells. An important feature of apoptosis is the requirement for adenosine triphosphate (ATP) to initiate the execution phase. In contrast, necrotic cell death is characterized by cell swelling and lysis. This is usually a consequence of profound loss of mitochondrial function and resultant ATP depletion, leading to loss of ion homeostasis, including volume regulation, and increased Ca2+. The latter activates a number of nonspecific hydrolases (i.e., proteases, nucleases, and phospholipases) as well as calcium dependent kinases. Activation of calpain I, the Ca2+-dependent cysteine protease cleaves the death-promoting Bcl-2 family members Bid and Bax which translocate to mitochondrial membranes, resulting in release of truncated apoptosis-inducing factor (tAIF), cytochrome c and endonuclease in the case of Bid and cytocrome c in the case of Bax. tAIF translocates to cell nuclei, and together with cyclophilin A and phosphorylated histone H2AX (γH2AX) is responsible for DNA cleavage, a feature of programmed necrosis. Activated calpain I has also been shown to cleave the plasma membrane Na+–Ca2+ exchanger, which leads to build-up of intracellular Ca2+, which is the source of additional increased intracellular Ca2+. Cytochrome c in cellular apoptosis is a component of the apoptosome.

DNA damage activates nuclear poly(ADP-ribose) polymerase-1(PARP-1), a DNA repair enzyme. PARP-1 forms poly(ADP-ribose) polymers, to repair DNA, but when DNA damage is extensive, PAR accumulates, exits cell nuclei and travels to mitochondrial membranes, where it, like calpain I, is involved in AIF release from mitochondria. A fundamental distinction between necrosis and apoptosis is the loss of plasma membrane integrity; this is integral to the former but not the latter. As a consequence, lytic release of cellular constituents promotes a local inflammatory reaction, whereas the rapid removal of apoptotic bodies minimizes such a reaction. The distinction between the two modes of death is easily accomplished *in vitro* but not *in vivo*. Thus, although claims that certain drugs induce apoptosis have been made, these are relatively unconvincing. DNA fragmentation can occur in necrosis, leading to positive TUNEL staining. Conversely, when apoptosis is massive, it can exceed the capacity for rapid phagocytosis, resulting in the eventual appearance of secondary necrosis.

Two alternative pathways - either extrinsic (receptor-mediated) or intrinsic (mitochondria-mediated) - lead to apoptotic cell death. The initiation of cell death begins either at the plasma membrane with the binding of TNF or FasL to their cognate receptors or within the

cell. The latter is due to the occurrence of intracellular stress in the form of biochemical events such as oxidative stress, redox changes, covalent binding, lipid peroxidation, and consequent functional effects on mitochondria, endoplasmic reticulum, microtubules, cytoskeleton, or DNA. The intrinsic mitochondrial pathway involves the initiator, caspase-9, which, when activated, forms an "apoptosome" in the cytosol, together with cytochrome c, which translocates from mitochondria, Apaf-1 and dATP. The apoptosome activates caspase-3, the central effector caspase, which in turn activates downstream factors that are responsible for the apoptotic death of a cell [1]. Intracellular stress either directly affects mitochondria or can lead to effects on other organelles, which then send signals to the mitochondria to recruit participation in the death process [1][2] Constitutively expressed nitric oxide synthase (nNOS) is a Ca2+-dependent cytosolic enzyme that forms nitric oxide (NO) from L-arginine, and NO reacts with the free radical such as superoxide (O2−) to form the very toxic free radical peroxynitrite (ONOO−). Free radicals such as ONOO−, O2 − and hydroxyl radical (OH−) damage cellular membranes and intracellular proteins, enzymes and DNA. [1][2][3][4]

How it is Measured or Detected

Necrosis:

LDH is a soluble cytoplasmic enzyme that is present in almost all cells and is released into extracellular space when the plasma membrane is damaged. To detect the leakage of LDH into cell culture medium, a tetrazolium salt is used in this assay. In the first step, LDH produces reduced nicotinamide adenine dinucleotide (NADH) when it catalyzes the oxidation of lactate to pyruvate. In the second step, a tetrazolium salt is converted to a colored formazan product using newly synthesized NADH in the presence of an electron acceptor. The amount of formazan product can be colorimetrically quantified by standard spectroscopy. Because of the linearity of the assay, it can be used to enumerate the percentage of necrotic cells in a sample. [5]

The MTT assay is a colorimetric assay for assessing cell viability. NAD(P)H-dependent cellular oxidoreductase enzymes may reflect the number of viable cells present. These enzymes are capable of reducing the tetrazolium dye MTT 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide to its insoluble formazan, which has a purple color. Other closely related tetrazolium dyes including XTT, MTS and the WSTs. Tetrazolium dye assays can also be used to measure cytotoxicity (loss of viable cells) or cytostatic activity (shift from proliferation to quiescence) of potential medicinal agents and toxic materials. MTT assays are usually done in the dark since the MTT reagent is sensitive to light [6].

Propidium iodide (PI) is an intercalating agent and a fluorescent molecule used to stain necrotic cells. It is cell membrane impermeant so it stains only those cells where the cell membrane is destroyed. When PI is bound to nucleic acids, the fluorescence excitation maximum is 535 nm and the emission maximum is 617 nm [7].

Alamar Blue (resazurin) fluorescent dye. The oxidized blue non fluorescent Alamar blue is reduced to a pink fluorescent dye in the medium by cell activity (O'Brien et al., 2000) (12).

Neutral red uptake, which is based on the ability of viable cells to incorporate and bind the supravital dye neutral red in lysosomes (Repetto et al., 2008)(13).

ATP assay: Quantification of ATP, signaling the presence of metabolically active cells (CellTiter-Glo; Promega).

Apoptosis:

TUNEL is a common method for detecting DNA fragmentation that results from apoptotic signalling cascades. The assay relies on the presence of nicks in the DNA which can be identified by terminal deoxynucleotidyl transferase or TdT, an enzyme that will catalyze the addition of dUTPs that are secondarily labeled with a marker. It may also label cells that have suffered severe DNA damage.

Caspase activity assays measured by fluorescence. During apoptosis, mainly caspase-3 and -7 cleave PARP to yield an 85 kDa and a 25 kDa fragment. PARP cleavage is considered to be one of the classical characteristics of apoptosis. Antibodies to the 85 kDa fragment of cleaved PARP or to caspase-3 both serve as markers for apoptotic cells that can be monitored using immunofluorescence [8].

Hoechst 33342 staining: Hoechst dyes are cell-permeable and bind to DNA in live or fixed cells. Therefore, these stains are often called supravital, which means that cells survive a treatment with these compounds. The stained, condensed or fragmented DNA is a marker of apoptosis. [9][10]

Acridine Orange/Ethidium Bromide staining is used to visualize nuclear changes and apoptotic body formation that are characteristic of apoptosis. Cells are viewed under a fluorescence microscope and counted to quantify apoptosis.

References

1. Fujikawa, D.G. (2015), The role of excitotoxic programmed necrosis in acute brain injury, Comput Struct Biotechnol J, vol. 13, pp. 212-221.
2. Malhi, H. et al. (2010), Hepatocyte death: a clear and present danger, Physiol Rev, vol. 90, no. 3, pp. 1165-1194.
3. Kaplowitz, N. (2002), Biochemical and Cellular Mechanisms of Toxic Liver Injury, Semin Liver Dis, vol. 22, no. 2, http://www.medscape.com/viewarticle/433631 (accessed on 20 January 2016).
4. Kroemer, G. et al., (2009), Classification of cell death: recommendations of the Nomenclature Committee on Cell Death, Cell Death Differ, vol. 16, no. 1, pp. 3-11.
5. Chan, F.K., K. Moriwaki and M.J. De Rosa (2013), Detection of necrosis by release of lactate dehydrogenase (LDH) activity, Methods Mol Biol, vol. 979, pp. 65–70.
6. Berridge, M.V., P.M. Herst and A.S. Tan (2005), Tetrazolium dyes as tools in cell biology: new insights into their cellular reduction. Biotechnology Annual Review, vol. 11, pp 127-152.
7. Moore, A, et al.(1998), Simultaneous measurement of cell cycle and apoptotic cell death,Methods Cell Biol, vol. 57, pp. 265–278.
8. Li, Peng et al. (2004), Mitochondrial activation of apoptosis, Cell, vol. 116, no. 2 Suppl,pp. S57-59, 2 p following S59.
9. Loo, D.T. (2002), TUNEL Assay an overview of techniques, Methods in Molecular Biology, vol. 203: In Situ Detection of DNA Damage, chapter 2, Didenko VV (ed.), Humana Press Inc.

10. Kubbies, M. and P.S. Rabinovitch (1983), Flow cytometric analysis of factors which influence the BrdUrd-Hoechst quenching effect in cultivated human fibroblasts and lymphocytes, Cytometry, vol. 3, no. 4, pp. 276–281.
11. Fink, S.L. and B.T. Cookson (2005), Apoptosis, pyroptosis, and necrosis: mechanistic description of dead and dying eukaryotic cells, Infect Immun, vol. 73, no. 4, pp.1907-1916.
12. O'Brien J, Wilson I, Orton T, Pognan F. 2000. Investigation of the Alamar Blue (resazurin) fluorescent dye for the assessment of mammalian cell cytotoxicity. European journal of biochemistry / FEBS 267(17): 5421-5426.
13. Repetto G, del Peso A, Zurita JL. 2008. Neutral red uptake assay for the estimation of cell viability/cytotoxicity. Nature protocols 3(7): 1125-1131.

Event: 188: N/A, Neuroinflammation

Short Name: N/A, Neuroinflammation

Key Event Component

Process	Object	Action
brain inflammation	microglial cell	pathological
brain inflammation	astrocyte	pathological

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	KeyEvent
Aop:48 - Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	KeyEvent
Aop:3 - Inhibition of the mitochondrial complex I of nigro-striatal neurons leads to parkinsonian motor deficits	KeyEvent
Aop:17 - Binding of electrophilic chemicals to SH(thiol)-group of proteins and /or to seleno-proteins during brain development leads to impairment of learning and memory	KeyEvent

Biological Context

Level of Biological Organization
Tissue

Organ term

Organ term
brain

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI
human	Homo sapiens	Moderate	NCBI

Neuroinflammation is observed in human, monkey, rat, mouse, and zebrafish, in association with neurodegeneration or following toxicant exposure. Some references (non-exhaustive list) are given below for illustration:

In human: Vennetti et al., 2006

In monkey (Macaca fascicularis): Charleston et al., 1994, 1996

Iin rat: Little et al., 2012; Zurich et al., 2002; Eskes et al., 2002

In mouse: Liu et al., 2012

In zebrafish: Xu et al., 2014.

Key Event Description

Neuroinflammation or brain inflammation differs from peripheral inflammation in that the vascular response and the role of peripheral bone marrow-derived cells are less conspicuous. The most easily detectable feature of neuroinflammation is activation of microglial cells and astrocytes. It is evidenced by changes in shape, increased expression of certain antigens, and accumulation and proliferation of the glial cells in affected regions (Aschner, 1998; Graeber & Streit, 1990; Monnet-Tschudi et al, 2007; Streit et al, 1999; Kraft and Harry, 2011; Claycomb et al., 2013). Upon stimulation by cytokines or inflammogens (e.g. from pathogens or from damaged neurons), both glial cell types activate inflammatory signalling pathways, which result in increased expression and/or release of inflammatory mediators such as cytokines, eicosanoids, and metalloproteinases (Dong & Benveniste, 2001), as well as in the production of reactive oxygen (ROS) and nitrogen species (RNS) (Brown & Bal-Price, 2003). Different types of activation states are possible for microglia and astrocytes, resulting in pro-inflammatory or anti-inflammatory signalling and other cellular functions (such as phagocytosis) (Streit et al., 1999; Nakajima and Kohsaka, 2004).

Therefore, neuroinflammation can have both neuroprotective/neuroreparative and neurodegenerative consequences (Carson et al., 2006 ; Monnet-Tschudi et al, 2007; Aguzzi et al., 2013 ; Glass et al., 2010). Under normal physiological conditions, microglial cells scan the nervous system for neuronal integrity (Nimmerjahn et al, 2005) and for invading pathogens (Aloisi, 2001; Kreutzberg, 1995; Kreutzberg, 1996; Rivest, 2009). They are the first type of cell activated (first line of defence), and can subsequently induce astrocyte activation (Falsig, 2008). Two distinct states of microglial activation have been described (Gordon, 2003; Kigerl et al, 2009; Maresz et al, 2008; Mosser & Edwards, 2008; Perego et al; Ponomarev et al, 2005): The M1 state is classically triggered by interferon-gamma and/or other pro-inflammatory cytokines, and this state is characterized by increased expression of integrin alpha M (Itgam) and CD86, as well as the release of pro-inflammatory cytokines (TNF-alpha, IL-1beta, IL-6), and it is mostly associated with neurodegeneration. The M2 state is triggered by IL-4 and IL-13 (Maresz et al, 2008; Perego et al, 2011; Ponomarev et al, 2007) and induces the expression of mannose receptor 1 (MRC1), arginase1 (Arg 1) and Ym1/2; it is involved in repair processes. The activation of astrocytes by microglia-derived cytokines or TLR agonists resembles the microglial M1 state (Falsig 2006). Although classification of the M1/M2 polarization of microglial cells may be considered as a simplification of authentic microglial reaction states (Ransohoff, 2016), a similar polarization of reactive astrocytes has been descibed recently Liddlelow et

al., 2017): Interleukin-1 alpha (IL-1α), TNF and subcomponent q (C1q) released by activated microglial cells induce A1-reactive astrocytes, which lose the ability to promote neuronal survival, outgrowth, synaptogenesis and phagocytosis and induce the death of neurons and oligodendrocytes.

How it is Measured or Detected

Neuroinflammation, i.e. the activation of glial cells can be measured by quantification of cellular markers (most commonly), or of released mediators (less common). As multiple activation states exist for the two main cell types involved, it is necessary to measure several markers of neuroinflammation:

1. Microglial activation can be detected based on the increased numbers of labeled microglia per volume element of brain tissue (due to increase of binding sites, proliferation, and immigration of cells) or on morphological changes. A specific microglial marker, used across different species, is CD11b. Alternatively various specific carbohydrate structures can be stained by lectins (e.g. IB4). Beyond that, various well-established antibodies are available to detect microglia in mouse tissue (F4/80), phagocytic microglia in rat tissue (ED1) or more generally microglia across species (Iba1). Transgenic mice are available with fluorescent proteins under the control of the CD11b promoter to easily quantify microglia without the need for specific stains.
2. The most frequently used astrocyte marker is GFAP (99% of all studies) (Eng et al., 2000). This protein is highly specific for astrocytes in the brain, and antibodies are available for immunocytochemical detection. In neuroinflamatory brain regions, the stain becomes more prominent, due to an upregulation of the protein, a shape change/proliferation of the cells, and/or better accessibility of the antibody. Various histological quantification approaches can be used. Occasionally, alternative astrocytic markers, such as vimentin of the S100beta protein, have been used for staining of astrocytes (Struzynska et al., 2007). Antibodies for complement component 3 (C3), the most characteristic and highly upregulated marker of A1 neurotoxic reactive astrocytes are commercially available.
3. All immunocytochemical methods can also be applied to cell culture models.
4. In patients, microglial accumulation can be monitored by PET imaging, using [11C]-PK 11195 as a microglial marker (Banati et al., 2002).
5. Activation of glial cells can be assessed in tissue or cell culture models also by quantification of sets of activation markers. This can for instance be done by PCR quantification of inflammatory factors, by measurement of the respective mediators, e.g. by ELISA-related immuno-quantification. Such markers include:
    - Pro- and anti-inflammatory cytokine expression (IL-1β; TNF-α, Il-6, IL-4); or expression of immunostimmulatory proteins (e.g. MHC-II)
    - Itgam, CD86 expression as markers of M1 microglial phenotype
    - Arg1, MRC1, as markers of M2 microglial phenotype

(for descriptions of techniques, see also Falsig 2004; Lund 2006 ; Kuegler 2010; Monnet-Tschudi et al., 2011; Sandström et al., 2014; von Tobel et al., 2014)

Regulatory example using the KE:Measurement of glial fibrillary acidic protein (GFAP) in brain tissue, whose increase is a marker of astrocyte reactivity, is required by the US EPA

in rodent toxicity studies for fuel additives (40 CFR 79.67), but is optional for other toxicant evaluations.

References

Aguzzi, A., Barres, B.A., Bennett, M.L., 2013. Microglia: scapegoat, saboteur, or something else? Science 339(6116), 156-161.

Aloisi, F., 2001. Immune function of microglia. Glia 36, 165-179.

Aschner M (1998) Immune and inflammatory responses in the CNS: modulation by astrocytes. ToxicolLett 103: 283-287

Banati, R. B. (2002). "Visualising microglial activation *in vivo*." Glia 40: 206-217.

Brown GC, Bal-Price A (2003) Inflammatory neurodegeneration mediated by nitric oxide, glutamate, and mitochondria. Mol Neurobiol 27: 325-355

Carson, M.J., Thrash, J.C., Walter, B., 2006. The cellular response in neuroinflammation: The role of leukocytes, microglia and astrocytes in neuronal death and survival. Clin Neurosci Res 6(5), 237-245.

Charleston JS, Body RL, Bolender RP, Mottet NK, Vahter ME, Burbacher TM. 1996. Changes in the number of astrocytes and microglia in the thalamus of the monkey Macaca fascicularis following long-term subclinical methylmercury exposure. NeuroToxicology 17: 127-138.

Charleston JS, Bolender RP, Mottet NK, Body RL, Vahter ME, Burbacher TM. 1994. Increases in the number of reactive glia in the visual cortex of Macaca fascicularis following subclinical long-term methyl mercury exposure. ToxicolApplPharmacol 129: 196-206.

Claycomb, K.I., Johnson, K.M., Winokur, P.N., Sacino, A.V., Crocker, S.J., 2013. Astrocyte regulation of CNS inflammation and remyelination. Brain Sci 3(3), 1109-1127.

Dong Y, Benveniste EN (2001) Immune Function of Astrocytes. Glia 36: 180-190

Eng LF, Ghirnikar RS, Lee YL (2000) Glial Fibrillary Acidic Protein: GFAP-Thirty-One Years (1969-2000). NeurochemRes 25: 1439-1451

Eskes C, Honegger P, Juillerat-Jeanneret L, Monnet-Tschudi F. 2002. Microglial reaction induced by noncytotoxic methylmercury treatment leads to neuroprotection via interactions with astrocytes and IL-6 release. Glia 37(1): 43-52.

Falsig J, Latta M, Leist M. Defined inflammatory states in astrocyte cultures correlation with susceptibility towards CD95-driven apoptosis. J Neurochem. 2004 Jan;88(1):181-93.

Falsig J, Pörzgen P, Lund S, Schrattenholz A, Leist M. The inflammatory transcriptome of reactive murine astrocytes and implications for their innate immune function. J Neurochem. 2006 Feb;96(3):893-907.

Falsig J, van Beek J, Hermann C, Leist M. Molecular basis for detection of invading pathogens in the brain. J Neurosci Res. 2008 May 15;86(7):1434-47.

Glass CK, Saijo K, Winner B, Marchetto MC, Gage FH (2010). Mechanisms underlying inflammation in neurodegeneration. Cell. 2010 Mar 19;140(6):918-34.

Gordon S (2003) Alternative activation of macrophages. Nat Rev Immunol 3: 23-35

Graeber MB, Streit WJ (1990) Microglia: immune network in the CNS. Brain Pathol 1: 2-5

Kigerl KA, Gensel JC, Ankeny DP, Alexander JK, Donnelly DJ, Popovich PG (2009) Identification of two distinct macrophage subsets with divergent effects causing either neurotoxicity or regeneration in the injured mouse spinal cord. J Neurosci 29: 13435-13444

Kraft AD, Harry GJ., Features of microglia and neuroinflammation relevant to environmental exposure and neurotoxicity. International Journal of Environmental research and Public Health., 2011, 8(7): 2980-3018.

Kreutzberg GW (1995) Microglia, the first line of defence in brain pathologies. Arzneimttelforsch 45: 357-360

Kreutzberg GW (1996) Microglia : a sensor for pathological events in the CNS. Trends Neurosci 19: 312-318

Kuegler PB, Zimmer B, Waldmann T, Baudis B, Ilmjärv S, Hescheler J, Gaughwin P, Brundin P, Mundy W, Bal-Price AK, Schrattenholz A, Krause KH, van Thriel C, Rao MS, Kadereit S, Leist M. Markers of murine embryonic and neural stem cells, neurons and astrocytes: reference points for developmental neurotoxicity testing. ALTEX. 2010;27(1):17-42

Liddelow SA, Guttenplan KA, Clarke LE, Bennett FC, Bohlen CJ, Schirmer L, et al. 2017. Neurotoxic reactive astrocytes are induced by activated microglia. Nature 541(7638): 481-487.

Little AR, Miller DB, Li S, Kashon ML, O'Callaghan JP. 2012. Trimethyltin-induced neurotoxicity: gene expression pathway analysis, q-RT-PCR and immunoblotting reveal early effects associated with hippocampal damage and gliosis. Neurotoxicol Teratol 34(1): 72-82.

Liu Y, Hu J, Wu J, Zhu C, Hui Y, Han Y, et al. 2012. alpha7 nicotinic acetylcholine receptor-mediated neuroprotection against dopaminergic neuron loss in an MPTP mouse model via inhibition of astrocyte activation. J Neuroinflammation 9: 98.

Lund S, Christensen KV, Hedtjärn M, Mortensen AL, Hagberg H, Falsig J, Hasseldam H, Schrattenholz A, Pörzgen P, Leist M. The dynamics of the LPS triggered inflammatory response of murine microglia under different culture and *in vivo* conditions. J Neuroimmunol. 2006 Nov;180(1-2):71-87.

Maresz K, Ponomarev ED, Barteneva N, Tan Y, Mann MK, Dittel BN (2008) IL-13 induces the expression of the alternative activation marker Ym1 in a subset of testicular macrophages. J Reprod Immunol 78: 140-148

Monnet-Tschudi F, Zurich MG, Honegger P (2007) Neurotoxicant-induced inflammatory response in three-dimensional brain cell cultures. Hum Exp Toxicol 26: 339-346

Monnet-Tschudi, F., A. Defaux, et al. (2011). "Methods to assess neuroinflammation." Curr Protoc Toxicol Chapter 12: Unit12 19.

Mosser DM, Edwards JP (2008) Exploring the full spectrum of macrophage activation. Nat Rev Immunol 8: 958-969

Nakajima K, Kohsaka S. 2004. Microglia: Neuroprotective and neurotrophic cells in the central nervous system. Current Drug Targets-Cardiovasc & Haematol Disorders 4: 65-84.

Perego C, Fumagalli S, De Simoni MG (2011) Temporal pattern of expression and colocalization of microglia/macrophage phenotype markers following brain ischemic injury in mice. J Neuroinflammation 8: 174

Ponomarev ED, Maresz K, Tan Y, Dittel BN (2007) CNS-derived interleukin-4 is essential for the regulation of autoimmune inflammation and induces a state of alternative activation in microglial cells. J Neurosci 27: 10714-10721

Ponomarev ED, Shriver LP, Maresz K, Dittel BN (2005) Microglial cell activation and proliferation precedes the onset of CNS autoimmunity. J Neurosci Res 81: 374-389

Ransohoff RM. 2016. A polarizing question: do M1 and M2 microglia exist? Nat Neurosci 19(8): 987-991.

Rivest, S., 2009. Regulation of innate immune responses in the brain. Nat Rev Immunol 9(6), 429-439.

Sandstrom von Tobel, J., D. Zoia, et al. (2014). "Immediate and delayed effects of subchronic Paraquat exposure during an early differentiation stage in 3D-rat brain cell cultures." Toxicol Lett. DOI : 10.1016/j.toxlet.2014.02.001

Streit, W.J., Walter, S.A., Pennell, N.A., 1999. Reactive microgliosis. Progress in Neurobiol. 57, 563-581.

Struzynska L, Dabrowska-Bouta B, Koza K, Sulkowski G (2007) Inflammation-Like Glial Response in Lead-Exposed Immature Rat Brain. Toxicol Sc 95:156-162

Venneti S, Lopresti BJ, Wiley CA. 2006. The peripheral benzodiazepine receptor (Translocator protein 18kDa) in microglia: from pathology to imaging. Prog Neurobiol 80(6): 308-322.

von Tobel, J. S., P. Antinori, et al. (2014). "Repeated exposure to Ochratoxin A generates a neuroinflammatory response, characterized by neurodegenerative M1 microglial phenotype." Neurotoxicology 44C: 61-70.

Xu DP, Zhang K, Zhang ZJ, Sun YW, Guo BJ, Wang YQ, et al. 2014. A novel tetramethylpyrazine bis-nitrone (TN-2) protects against 6-hydroxyldopamine-induced neurotoxicity via modulation of the NF-kappaB and the PKCalpha/PI3-K/Akt pathways. Neurochem Int 78: 76-85.

Zurich M-G, Eskes C, Honegger P, Bérode M, Monnet-Tschudi F. 2002. Maturation-dependent neurotoxicity of lead aceate *in vitro*: Implication of glial reactions. J Neurosc Res 70: 108-116.

List of AO(s) in the AOP

Event: 352: N/A, Neurodegeneration

Short Name: N/A, Neurodegeneration

Key Event Component

Process	Object	Action
neurodegeneration		increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	AdverseOutcome
Aop:48 - Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	KeyEvent

Biological Context

Level of Biological Organization
Tissue

Organ term

Organ term
brain

Domain of Applicability

The necrotic and apoptotic cell death pathways are quite well conserved throughout taxa (Blackstone and Green, 1999, Aravind et al., 2001). It has been widely suggested that apoptosis is also conserved in metazoans, although despite conservation of Bcl-2 proteins, APAF-1, and caspases there is no biochemical evidence of the existence of the mitochondrial pathway in either C. elegans or Drosophila apoptosis (Baum et al., 2007; Blackstone and Green, 1999).

Key Event Description

The term neurodegeneration is a combination of two words - "neuro," referring to nerve cells and "degeneration," referring to progressive damage. The term "neurodegeneration" can be applied to several conditions that result in the loss of nerve structure and function, and neuronal loss by necrosis and/or apoptosis

Neurodegeneration is a key aspect of a large number of diseases that come under the umbrella of “neurodegenerative diseases" including Huntington's, Alzheimer’s and Parkinson’s disease. All of these conditions lead to progressive brain damage and neurodegeneration.

Alzheimer's disease is characterised by loss of neurons and synapses in the cerebral cortex and certain subcortical regions, with gross atrophy of the affected regions; symptoms include memory loss.

Parkinson's disease (PD) results from the death of dopaminergic neurons in the midbrain substantia nigra pars compacta; symptoms include bradykinesia, rigidity, and resting tremor.

Several observations suggest correlative links between environmental exposure and neurodegenerative diseases, but only few suggest causative links:

Only an extremely small proportion (less than 5%) of neurodegenerative diseases are caused by genetic mutations (Narayan and Dragounov, 2017). The remainders are thought to be caused by the following:

- A build up of toxic proteins in the brain (Evin et al., 2006)
- A loss of mitochondrial function that leads to the oxidative stress and creation of neurotoxic molecules that trigger cell death (apoptotic, necrotic or autophagy) (Cobley et al., 2018)
- Changes in the levels and activities of neurotrophic factors (Kazim and Iqbal, 2016; Machado et al., 2016; Rodriguez et al., 2014)
- Variations in the activity of neural networks (Greicius and Kimmel, 2012)

Protein aggregation: the correlation between neurodegenerative disease and protein aggregation in the brain has long been recognised, but a causal relationship has not been unequivocally established (Lansbury et al., 2006; Kumar et al., 2016). The dynamic nature of protein aggregation mean that, despite progress in understanding its mechanisms, its relationship to disease is difficult to determine in the laboratory.

Nevertheless, drug candidates that inhibit aggregation are now being tested in the clinic. These have the potential to slow the progression of Alzheimer's disease, Parkinson's disease and related disorders and could, if administered pre-symptomatically, drastically reduce the incidence of these diseases.

Loss of mitochondrial function: many lines of evidence suggest that mitochondria have a central role in neurodegenerative diseases (Lin and Beal, 2006). Mitochondria are critical regulators of cell death, a key feature of neurodegeneration. Dysfunction of mitochondria induces oxidative stress, production of free radicals, calcium overload, and mutations in mitochondrial DNA that contribute to neurodegenerative diseases. In all major examples of these diseases there is strong evidence that mitochondrial dysfunction occurs early and acts causally in disease pathogenesis. Moreover, an impressive number of disease- specific proteins interact with mitochondria. Thus, therapies targeting basic mitochondrial

processes, such as energy metabolism or free-radical generation, or specific interactions of disease-related proteins with mitochondria, hold great promise.

Decreased level of neurotrophic factors: decreased levels and activities of neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), have been described in a number of neurodegenerative disorders, including Huntington's disease, Alzheimer disease and Parkinson disease (Zuccato and Cattaneo, 2009). These studies have led to the development of experimental strategies aimed at increasing BDNF levels in the brains of animals that have been genetically altered to mimic the aforementioned human diseases, with a view to ultimately influencing the clinical treatment of these conditions. Therefore BDNF treatment is being considered as a beneficial and feasible therapeutic approach in the clinic.

Variations in the activity of neural networks: Patients with various neurodegenerative disorders show remarkable fluctuations in neurological functions, even during the same day (Palop et al., 2006). These fluctuations cannot be caused by sudden loss or gain of nerve cells. Instead, it is likely that they reflect variations in the activity of neural networks and, perhaps, chronic intoxication by abnormal proteins that the brain is only temporarily able to overcome.

How it is Measured or Detected

The assays for measurements of necrotic or apoptotic cell death are described in the Key Event: Cell injury/Cell death

Recent neuropathological studies have shown that Fluoro-Jade, an anionic fluorescent dye, is a good marker of degenerating neurons. Fluoro-Jade and Fluoro-Jade B were found to stain all degenerating neurons, regardless of specific insult or mechanism of cell death (Schmued et al., 2005). More recently, Fluoro-Jade C was shown to be highly resistant to fading and compatible with virtually all histological processing and staining protocols (Schmued et al., 2005). In addition, Fluoro-Jade C is a good tool for detecting acutely and chronically degenerating neurons (Ehara and Ueda, 2009).

Regulatory Significance of the AO

Currently the four available OECD Test Guidelines (TGs) for neurotoxicity testing are entirely based on *in vivo* neurotoxicity studies: (1)Delayed Neurotoxicity of Organophosphorus Substances Following Acute Exposure (TG 418); (2) Delayed Neurotoxicity of Organophosphorus Substances: 28-day Repeated Dose Study (TG 419); (3) Neurotoxicity Study in Rodents (TG 424) involves daily oral dosing of rats for acute, subchronic, or chronic assessments (28 days, 90 days, or one year or longer); (4) Developmental Neurotoxicity (DNT) Study (TG 426) evaluates in utero and early postnatal effects by daily dosing of at least 60 pregnant rats from implantation through lactation. One of the endpoints required by all four of these OECD TGs is evaluation of neurodegeneration that, so far, is performed through *in vivo* neuropathological and histological studies. Therefore, neurodegeneration described in this AOP as a key event, has a regulatory relevance and could be performed using *in vitro* assays that allow a reliable evaluation of neurodegeneration using a large range of existing assays, specific for apoptosis, necrosis and autophagy (see also KE Cell injury/Cell death).

References

Aravind, L., Dixit, V. M., and Koonin, E. V. (2001). Apoptotic Molecular Machinery: Vastly Increased Complexity in Vertebrates Revealed by Genome Comparisons. Science 291, 1279-1284.

Baum, J. S., Arama, E., Steller, H., and McCall, K. (2007). The Drosophila caspases Strica and Dronc function redundantly in programmed cell death during oogenesis. Cell Death Differ 14, 1508-1517.

Blackstone, N. W., and Green, D. R. (1999). The evolution of a mechanism of cell suicide. Bioessays 21, 84-88.

Cobley JN, Fiorello ML, Bailey DM (2018) 13 reasons why the brain is susceptible to oxidative stress. Redox Biol 15: 490-503

Ehara A, Ueda S. 2009. Application of Fluoro-Jade C in acute and chronic neurodegeneration models: utilities and staining differences. Acta histochemica et cytochemica 42(6): 171-179.

Evin G, Sernee MF, Masters CL (2006) Inhibition of gamma-secretase as a therapeutic intervention for Alzheimer's disease: prospects, limitations and strategies. CNS Drugs 20: 351-72

Greicius MD, Kimmel DL (2012) Neuroimaging insights into network-based neurodegeneration. Curr Opin Neurol 25: 727-34

Kazim SF, Iqbal K (2016) Neurotrophic factor small-molecule mimetics mediated neuroregeneration and synaptic repair: emerging therapeutic modality for Alzheimer's disease. Mol Neurodegener 11: 50

Kumar V, Sami N, Kashav T, Islam A, Ahmad F, Hassan MI (2016) Protein aggregation and neurodegenerative diseases: From theory to therapy. Eur J Med Chem 124: 1105-1120

Lansbury1 PT & Lashuel HA (2006) A century-old debate on protein aggregation and neurodegeneration enters the clinic. Nature 443, 774-779.

Lin1 MT & Beal MF (2006) Mitochondrial dysfunction and oxidative stress in neurodegenerative diseases. Nature 443, 787-795

Machado V, Zoller T, Attaai A, Spittau B (2016) Microglia-Mediated Neuroinflammation and Neurotrophic Factor-Induced Protection in the MPTP Mouse Model of Parkinson's Disease-Lessons from Transgenic Mice. Int J Mol Sci 17

Narayan P, Dragunow M (2017) Alzheimer's Disease and Histone Code Alterations. Adv Exp Med Biol 978: 321-336

Palop JJ, Chin1 J & Mucke L, Review Article A network dysfunction perspective on neurodegenerative diseases. 2006, Nature 443, 768-773

Rodrigues TM, Jeronimo-Santos A, Outeiro TF, Sebastiao AM, Diogenes MJ (2014) Challenges and promises in the development of neurotrophic factor-based therapies for Parkinson's disease. Drugs Aging 31: 239-61

Schmued LC, Stowers CC, Scallet AC, Xu L. 2005. Fluoro-Jade C results in ultra high resolution and contrast labeling of degenerating neurons. Brain Res 1035(1): 24-31.

Zuccato C & Cattaneo E, Brain-derived neurotrophic factor in neurodegenerative diseases.2009, Nature Reviews Neurology 5, 311-3

List of AO(s) in the AOP

Event: 341: Impairment, Learning and memory

Short Name: Impairment, Learning and memory

Key Event Component

Process	Object	Action
learning		decreased
memory		decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:13 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	AdverseOutcome
Aop:48 - Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	AdverseOutcome
Aop:54 - Inhibition of Na+/I- symporter (NIS) leads to learning and memory impairment	AdverseOutcome
Aop:77 - Nicotinic acetylcholine receptor activation contributes to abnormal foraging and leads to colony death/failure 1	KeyEvent
Aop:78 - Nicotinic acetylcholine receptor activation contributes to abnormal role change within the worker bee caste leading to colony death failure 1	KeyEvent
Aop:87 - Nicotinic acetylcholine receptor activation contributes to abnormal foraging and leads to colony loss/failure	KeyEvent
Aop:88 - Nicotinic acetylcholine receptor activation contributes to abnormal foraging and leads to colony loss/failure via abnormal role change within caste	KeyEvent
Aop:89 - Nicotinic acetylcholine receptor activation followed by desensitization contributes to abnormal foraging and directly leads to colony loss/failure	KeyEvent
Aop:90 - Nicotinic acetylcholine receptor activation contributes to abnormal roll change within the worker bee caste leading to colony loss/failure 2	KeyEvent
Aop:12 - Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	AdverseOutcome
Aop:99 - Histamine (H2) receptor antagonism leading to reduced survival	KeyEvent
Aop:17 - Binding of electrophilic chemicals to SH(thiol)-group of proteins and /or to seleno-proteins during brain development leads to impairment of learning and memory	AdverseOutcome

Biological Context

Level of Biological Organization
Individual

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
fruit fly	Drosophila melanogaster	High	NCBI
zebrafish	Danio rerio	High	NCBI
gastropods	Physa heterostropha	High	NCBI

Life Stage Applicability

Life Stage	Evidence
During brain development	High

Sex Applicability

Sex	Evidence
Mixed	High

Basic forms of learning behavior such as habituation have been found in many taxa from worms to humans (Alexander, 1990). More complex cognitive processes such as executive function likely reside only in higher mammalian species such as non-human primates and humans. Recently, larval zebrafish has also been suggested as a model for the study of learning and memory (Roberts et al., 2013).

Key Event Description

Learning can be defined as the process by which new information is acquired to establish knowledge by systematic study or by trial and error (Ono, 2009). Two types of learning are considered in neurobehavioral studies: a) associative learning and b) non-associative learning. Associative learning is based on making associations between different events. In associative learning, a subject learns the relationship among two different stimuli or between the stimulus and the subject's behaviour. On the other hand, non-associative learning can be defined as an alteration in the behavioural response that occurs over time

in response to a single type of stimulus. Habituation and sensitization are some examples of non-associative learning.

The memory formation requires acquisition, retention and retrieval of information in the brain, which is characterised by the non-conscious recall of information (Ono, 2009). There are three main categories of memory, including sensory memory, short-term or working memory (up to a few hours) and long-term memory (up to several days or even much longer).

Learning and memory depend upon the coordinated action of different brain regions and neurotransmitter systems constituting functionally integrated neural networks (D'Hooge and DeDeyn, 2001). Among the many brain areas engaged in the acquisition of, or retrieval of, a learned event, the hippocampal-based memory systems have received the most study. For example, the hippocampus has been shown to be critical for spatial-temporal memory, visio-spatial memory, verbal and narrative memory, and episodic and autobiographical memory (Burgess et al., 2000; Vorhees and Williams, 2014). However, there is substantial evidence that fundamental learning and memory functions are not mediated by the hippocampus alone but require a network that includes, in addition to the hippocampus, anterior thalamic nuclei, mammillary bodies cortex, cerebellum and basal ganglia (Aggleton and Brown, 1999; Doya, 2000; Mitchell et al., 2002, Toscano and Guilarte, 2005; Gilbert et al., 2006, 2016). Thus, damage to variety of brain structures can potentially lead to impairment of learning and memory. The main learning areas and pathways are similar in rodents and primates, including man (Eichenbaum, 2000; Stanton and Spear, 1990).

For the purposes of this KE (AO), impaired learning and memory is defined as an organism's inability to establish new associative or non-associative relationships, or sensory, short-term or long-term memories which can be measured using different behavioural tests described below.

How it is Measured or Detected

In laboratory animals: in rodents, a variety of tests of learning and memory have been used to probe the integrity of hippocampal function. These include tests of spatial learning like the radial arm maze (RAM), the Barnes maze, passive avoidance and Spontaneous alternation and most commonly, the Morris water maze (MWM). Test of novelty such as novel object recognition, and fear based context learning are also sensitive to hippocampal disruption. Finally, trace fear conditioning which incorporates a temporal component upon traditional amygdala-based fear learning engages the hippocampus. A brief description of these tasks follows.

1) RAM, Barnes, MWM are examples of spatial tasks, animals are required to learn the location of a food reward (RAM); an escape hole to enter a preferred dark tunnel from a brightly lit open field area (Barnes maze), or a hidden platform submerged below the surface of the water in a large tank of water (MWM) (Vorhees and Williams, 2014).

2) Novel Object recognition. This is a simpler task that can be used to probe recognition memory. Two objects are presented to animal in an open field on trial 1, and these are explored. On trial 2, one object is replaced with a novel object and time spent interacting with the novel object is taken evidence of memory retention – I have seen one of these objects before, but not this one (Cohen and Stackman, 2015).

3) Contextual Fear conditioning is a hippocampal based learning task in which animals are placed in a novel environment and allowed to explore for several minutes before delivery of an aversive stimulus, typically a mild foot shock. Upon reintroduction to this same environment in the future (typically 24-48 hours after original training), animals will limit their exploration, the context of this chamber being associated with an aversive event. The degree of suppression of activity after training is taken as evidence of retention, i.e., memory (Curzon et al., 2009).

4) Trace fear conditioning. Standard fear conditioning paradigms require animals to make an association between a neutral conditioning stimulus (CS, a light or a tone) and an aversive stimulus (US, a footshock). The unconditioned response (CR) that is elicited upon delivery of the footshock US is freezing behavior. With repetition of CS/US delivery, the previously neutral stimulus comes to elicit the freezing response. This type of learning is dependent on the amygdala, a brain region associated with, but distinct from the hippocampus. Introducing a brief delay between presentation of the neutral CS and the aversive US, a trace period, requires the engagement of the amygdala and the hippocampus (Shors et al., 2001).

In humans: A variety of standardized learning and memory tests have been developed for human neuropsychological testing, including children (Rohlman et al., 2008). These include episodic autobiographical memory, perceptual motor tests, short and long term memory tests, working memory tasks, word pair recognition memory; object location recognition memory. Some have been incorporated in general tests of intelligence (IQ) such as the WAIS and the Wechsler. Modifications have been made and norms developed for incorporating of tests of learning and memory in children. Examples of some of these tests include:

1) Rey Osterieth Complex Figure (RCFT) which probes a variety of functions including as visuospatial abilities, memory, attention, planning, and working memory (Shin et al., 2006).

2) Children's Auditory Verbal Learning Test (CAVLT) is a free recall of presented word lists that yields measures of Immediate Memory Span, Level of Learning, Immediate Recall, Delayed Recall, Recognition Accuracy, and Total Intrusions. (Lezak 1994; Talley, 1986).

3) Continuous Visual Memory Test (CVMT) measures visual learning and memory. It is a free recall of presented pictures/objects rather than words but that yields similar measures of Immediate Memory Span, Level of Learning, Immediate Recall, Delayed Recall, Recognition Accuracy, and Total Intrusions. (Lezak, 1984; 1994).

4) Story Recall from Wechsler Memory Scale (WMS) Logical Memory Test Battery, a standardized neurospychological test designed to measure memory functions (Lezak, 1994; Talley, 1986).

5) Autobiographical memory (AM) is the recollection of specific personal events in a multifaceted higher order cognitive process. It includes episodic memory- remembering of past events specific in time and place, in contrast to semantic autobiographical memory is the recollection of personal facts, traits, and general knowledge. Episodic AM is associated with greater activation of the hippocampus and a later and more gradual developmental trajectory. Absence of episodic memory in early life (infantile amnesia) is thought to reflect immature hippocampal function (Herold et al., 2015; Fivush, 2011).

6) Staged Autobiographical Memory Task. In this version of the AM test, children participate in a staged event involving a tour of the hospital, perform a series of tasks (counting footprints in the hall, identifying objects in wall display, buy lunch, watched a video). It is designed to contain unique event happenings, place, time, visual/sensory/perceptual details. Four to five months later, interviews are conducted using Children's Autobiographical Interview and scored according to standardized scheme (Willoughby et al., 2014).

Regulatory Significance of the AO

A prime example of impairments in learning and memory as the adverse outcome for regulatory action is developmental lead exposure and IQ function in children (Bellinger, 2012). Most methods are well established in the published literature and many have been engaged to evaluate the effects of developmental thyroid disruption. The US EPA and OECD Developmental Neurotoxicity (DNT) Guidelines (OCSPP 870.6300 or OECD 426) both require testing of learning and memory (USEPA, 1998; OECD, 2007) advising to use the following tests passive avoidance, delayed-matching-to-position for the adult rat and for the infant rat, olfactory conditioning, Morris water maze, Biel or Cincinnati maze, radial arm maze, T-maze, and acquisition and retention of schedule-controlled behaviour. These DNT Guidelines have been deemed valid to identify developmental neurotoxicity and adverse neurodevelopmental outcomes (Makris et al., 2009).

Also in the frame of the OECD GD 43 (2008) on reproductive toxicity, learning and memory testing may have potential to be applied in the context of developmental neurotoxicity studies. However, many of the learning and memory tasks used in guideline studies may not readily detect subtle impairments in cognitive function associated with modest degrees of developmental thyroid disruption (Gilbert et al., 2012).

References

Aggleton JP, Brown MW. (1999) Episodic memory, amnesia, and the hippocampal-anterior thalamic axis. Behav Brain Sci. 22: 425-489.

Alexander RD (1990) Epigenetic rules and Darwinian algorithms: The adaptive study of learning and development. Ethology and Sociobiology 11:241-303.

Bellinger DC (2012) A strategy for comparing the contributions of environmental chemicals and other risk factors to neurodevelopment of children. Environ Health Perspect 120:501-507.

Burgess N (2002) The hippocampus, space, and viewpoints in episodic memory. Q J Exp Psychol A 55:1057-1080. Cohen, SJ and Stackman, RW. (2015). Assessing rodent hippocampal involvement in the novel object recognition task. A review. Behav. Brain Res. 285: 105-1176.

Cohen, SJ and Stackman, RW. (2015). Assessing rodent hippocampal involvement in the novel object recognition task. A review. Behav. Brain Res. 285: 105-1176.

Curzon P, Rustay NR, Browman KE. Cued and Contextual Fear Conditioning for Rodents. In: Buccafusco JJ, editor. Methods of Behavior Analysis in Neuroscience. 2nd edition. Boca Raton (FL): CRC Press/Taylor & Francis; 2009.

D'Hooge R, De Deyn PP (2001) Applications of the Morris water maze in the study of learning and memory. Brain Res Brain Res Rev 36:60-90.

Doya K. (2000) Complementary roles of basal ganglia and cerebellum in learning and motor control. Curr Opin Neurobiol. 10: 732-739.

Eichenbaum H (2000) A cortical-hippocampal system for declarative memory. Nat Rev Neurosci 1:41-50.

Fivush R. The development of autobiographical memory. Annu Rev Psychol. 2011;62:559-82.

Gilbert ME, Sanchez-Huerta K, Wood C (2016) Mild Thyroid Hormone Insufficiency During Development Compromises Activity-Dependent Neuroplasticity in the Hippocampus of Adult Male Rats. Endocrinology 157:774-787.

Gilbert ME, Rovet J, Chen Z, Koibuchi N. (2012) Developmental thyroid hormone disruption: prevalence, environmental contaminants and neurodevelopmental consequences. Neurotoxicology 33: 842-52.

Gilbert ME, Sui L (2006) Dose-dependent reductions in spatial learning and synaptic function in the dentate gyrus of adult rats following developmental thyroid hormone insufficiency. Brain Res 1069:10-22.

Herold, C, Lässer, MM, Schmid, LA, Seidl, U, Kong, L, Fellhauer, I, Thomann,PA, Essig, M and Schröder, J. (2015). Neuropsychology, Autobiographical Memory, and Hippocampal Volume in “Younger” and “Older” Patients with Chronic Schizophrenia. Front. Psychiatry, 6: 53.

Lezak MD (1984) Neuropsychological assessment in behavioral toxicology--developing techniques and interpretative issues. Scand J Work Environ Health 10 Suppl 1:25-29.

Lezak MD (1994) Domains of behavior from a neuropsychological perspective: the whole story. Nebr Symp Motiv 41:23-55.

Makris SL, Raffaele K, Allen S, Bowers WJ, Hass U, Alleva E, Calamandrei G, Sheets L, Amcoff P, Delrue N, Crofton KM. (2009) A retrospective performance assessment of the developmental neurotoxicity study in support of OECD test guideline 426. Environ Health Perspect. 117(1):17-25.

Mitchell AS, Dalrymple-Alford JC, Christie MA. (2002) Spatial working memory and the brainstem cholinergic innervation to the anterior thalamus. J Neurosci. 22: 1922-1928.

OECD. 2007. OECD guidelines for the testing of chemicals/ section 4: Health effects. Test no. 426: Developmental neurotoxicity study. www.Oecd.Org/dataoecd/20/52/37622194.Pdf [accessed may 21, 2012].

OECD (2008) Nr 43 GUIDANCE DOCUMENT ON MAMMALIAN REPRODUCTIVE TOXICITY TESTING AND ASSESSMENT. ENV/JM/MONO(2008)16

Ono T. (2009) Learning and Memory. Encyclopedia of neuroscience. M D. Binder, N. Hirokawa and U. Windhorst (Eds). Springer-Verlag GmbH Berlin Heidelberg. pp 2129-2137.

Roberts AC, Bill BR, Glanzman DL. (2013) Learning and memory in zebrafish larvae. Front Neural Circuits 7: 126.

Rohlman DS, Lucchini R, Anger WK, Bellinger DC, van Thriel C. (2008) Neurobehavioral testing in human risk assessment. Neurotoxicology. 29: 556-567.

Shin, MS, Park, SY, Park, SR, Oeol, SH and Kwon, JS. (2006). Clinical and empirical applications of the Rey-Osterieth complex figure test. Nature Protocols, 1: 892-899.

Shors TJ, Miesegaes G, Beylin A, Zhao M, Rydel T, Gould E (2001) Neurogenesis in the adult is involved in the formation of trace memories. Nature 410:372-376.

Stanton ME, Spear LP (1990) Workshop on the qualitative and quantitative comparability of human and animal developmental neurotoxicity, Work Group I report: comparability of measures of developmental neurotoxicity in humans and laboratory animals. Neurotoxicol Teratol 12:261-267.

Talley, JL. (1986). Memory in learning disabled children: Digit span and eh Rey Auditory verbal learning test. Archives of Clinical Neuropsychology, Elseiver.

Toscano CD, Guilarte TR. (2005) Lead neurotoxicity: From exposure to molecular effects. Brain Res Rev. 49: 529-554.

U.S.EPA. 1998. Health effects guidelines OPPTS 870.6300 developmental neurotoxicity study. EPA Document 712-C-98-239.Office of Prevention Pesticides and Toxic Substances.

Vorhees CV, Williams MT (2014) Assessing spatial learning and memory in rodents. ILAR J 55:310-332.

Willoughby KA, McAndrews MP, Rovet JF. Accuracy of episodic autobiographical memory in children with early thyroid hormone deficiency using a staged event. Dev Cogn Neurosci. 2014 Jul;9:1-11.

Appendix 2: List of Key Event Relationships (KERs) in the AOP

List of Adjacent Key Event Relationships

Relationship: 229: Binding of antagonist, NMDA receptors leads to Inhibition, NMDARs

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	adjacent	High	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	High	

Evidence Supporting Applicability of this Relationship

The biophysical properties of rat and human receptors have been mostly assessed through recombinant studies, whereas the pharmacological properties of rat and human NMDA receptors have not been fully explored and compared yet (Hedegaard et al., 2012). Mean channel open times for human NMDA receptor subtypes in recombinant protein studies are similar to those of the corresponding rat NMDA receptor subtypes. However, mean single-channel conductances for human NMDA receptor subtypes appear lower than those of the corresponding rat NMDA receptor subtypes. Regarding pharmacological properties of the receptors, the differences were less than 2-fold and were not observed at the same subtypes for all the antagonists tested, suggesting that the molecular pharmacology of NMDA receptor is conserved between human and rat, although some inter-species differences are seen in IC50 values using two-electrode voltage-clamp recordings (Hedegaard et al., 2012).

Key Event Relationship Description

It is well documented that prolonged/chronic antagonism of NMDARs triggers the downstream KE named inhibition of NMDARs. Shorter term binding to the same receptors may trigger different downstream KEs, such as up-regulation of the NMDARs, resulting in toxic increased influx of calcium and to cell death. Consequently, this information can be captured in other KERs and AOP.

Evidence Supporting this KER

Biological Plausibility

There is structural mechanistic understanding supporting the relationship between MIE (NMDARs, binding of antagonists) and KE (NMDARs, inhibition). Crystal structure studies are used to study the binding of antagonists/agonists to NMDA receptors. In case of NMDAR antagonists, the binding to the receptor causes LBD conformation changes which promote channel closure leading to reduced Ca+2 influx (Blanke and VanDongen, 2009). This lack of measurable ion flux is applied as an indication of NMDAR inhibition.

Empirical Evidence

In slices of cerebellum derived from postnatal days 6-30 (PND 6-30) Sprague Dawley rats, 10 µM MK-801 completely blocked evoked NMDA excitatory postsynaptic currents (EPSCs) as it has been demonstrated by patch clamp technique (Rumbaugh and Vicini, 1999). The same technique has been employed in cortical slices from C57BL/6 mice of both genders and different age groups (P8-12, P21-28 or P45-90), showing that 1 µM APV and 50 nM NVP-AAM077 antagonise a similar amount of NMDA receptor current independently of the age (de Marchena et al., 2008).

Pb acts as a non-competitive, voltage independent antagonist of NMDAR. Pb action partially overlaps with that of zinc (Gavazzo et al., 2008)

Pb2+ has potent inhibitory effects on the NMDA receptor (Alkondon et al., 1990; Guilarte and Miceli, 1992; Guilarte, 1997; Gavazzo et al., 2001). In rat hippocampal neurons, Pb2+ (2.5-50 µM) inhibits NMDA-induced whole-cell and single-channel currents in a concentration-dependent manner, suggesting that Pb2+ can decrease the frequency of NMDA-induced channel activation (Alkondon et al., 1990). In the same study, they have examined the effect of Pb2+ on the binding of [3H]MK-801 to the rat brain hippocampal membranes and showed that Pb2+ inhibits the binding of [3H]-MK-801 in a concentration dependent manner with an IC50 value close to 7 µM (Alkondon et al., 1990). These inhibitory effects of Pb2+ on NMDA receptors activation appear to be age and brain region specific (Guilarte, 1997; Guilarte and Miceli, 1992). The Pb2+ IC50 is significantly lower in cortical membranes prepared from neonatal than from adult rats, whereas the hippocampus is more sensitive than the cerebral cortex since the Pb2+ IC50 is significantly lower in the hippocampus (Guilarte and Miceli, 1992). The number of [3H]-MK-801 binding sites associated with the high and low affinity sites of Pb2+ inhibition in the hippocampus of rats is increased as a function of age, peaking at PND 28 and 21 (Guilarte, 1997). High and low affinity Pb(2+)-sensitive [3H]-MK-801 binding sites have also been measured in the cerebral cortex during early development, but that has not been possible to evaluate after PND 14.

The developing brain is more sensitive than the adult brain to Pb2+-induced effects mediated through the NMDA receptor. Moreover, the hippocampus appears to be particularly vulnerable as in this brain structure NMDA receptors undergo subunit specific changes during developmental Pb2+ exposure (Guilarte and McGlothan, 1998). Exposure to Pb2+ during synaptogenesis causes decreased expression of hippocampal NR2A-subunit of NMDARs at synapses and increased targeting of NR2B-NMDARs to dendritic spines (without increased NR2B-NMDARs expression) (Nihei and Guilarte, 1999; Neal et al., 2011; Zhang et al., 2002).

Uncertainties and Inconsistencies

Pb2+ has been found to produce either potentiation or inhibition depending on: a) the subunit composition of NMDA receptors, b) endogenous glutamate concentration and c) Pb2+ dosage. In case that the NMDA receptors are saturated by agonist, Pb2+ at low concentrations (<1 μM) acts as a positive modulator of agonist action at NR1b-2AC and NR1a-2AB subunit complexes, whereas at higher concentrations, Pb2+ it behaves as a potent inhibitor of all recombinant NMDA receptors tested and was least potent at NR1b-2AC (Omelchenko et al., 1996; 1997), meaning that Pb2+ is not always acting as NMDAR inhibitor but it can also behave as NMDAR activator under certain conditions.

References

Alkondon M, Costa AC, Radhakrishnan V, Aronstam RS, Albuquerque EX. (1990) Selective blockade of NMDA-activated channel currents may be implicated in learning deficits caused by lead. FEBS Lett. 261: 124-130.

Blanke ML, VanDongen AMJ. (2009) Activation Mechanisms of the NMDA Receptor. In: Van Dongen AM, editor. Biology of the NMDA Receptor. Boca Raton (FL): CRC Press; Chapter 13. Available from: http://www.ncbi.nlm.nih.gov/books/NBK5274/

de Marchena J, Roberts AC, Middlebrooks PG, Valakh V, Yashiro K, Wilfley LR, Philpot BD. (2008) NMDA receptor antagonists reveal age-dependent differences in the properties of visual cortical plasticity. J Neurophysiol. 100: 1936-1948.

Gavazzo P, Gazzoli A, Mazzolini M, Marchetti C. (2001) Lead inhibition of NMDA channels in native and recombinant receptors. NeuroReport. 12: 3121-3125.

Gavazzo P, Zanardi I, Baranowska-Bosiacka I, Marchetti C. (2008) Molecular determinants of Pb2+ interaction with NMDA receptor channels. Neurochem Int. 52: 329-337.

Guilarte TR, Miceli RC. (1992) Age-dependent effects of lead on [3H]-MK-801 binding to the NMDA receptor-gated ionophore: *In vitro* and *in vivo* studies. Neurosci Lett. 148: 27-30.

Guilarte TR. (1997) Pb2+ Inhibits Nmda Receptor Function at High and Low Affinity Sites: Developmental and Regional Brain Expression. Neurotoxicology 18: 43-51.

Guilarte TR, McGlothan JL. (1998) Hippocampal NMDA Receptor mRNA Undergoes Subunit Specific Changes During Developmental Lead Exposure. Brain Res. 790: 98-107.

Hedegaard MK, Hansen KB, Andersen KT, Bräuner-Osborne H, Traynelis SF. (2012) Molecular pharmacology of human NMDA receptors. Neurochem Int. 61: 601-609.

Lasley SM, Gilbert ME. (1999) Lead inhibits the rat N-methyl-d-aspartate receptor channel by binding to a site distinct from the zinc allosteric site. Toxicol Appl Pharmacol. 159: 224-233.

MacDonald JF, Jackson MF, Beazely MA. (2006) Hippocampal long-term synaptic plasticity and signal amplification of NMDA receptors. Crit Rev Neurobiol. 18: 71-84.

Neal AP, Worley PF, Guilarte TR. (2011) Lead exposure during synaptogenesis alters NMDA receptor targeting via NMDA receptor inhibition. Neurotoxicology 32: 281-289.

Nihei MK, Guilarte TR. (1999) NMDAR-2A subunit protein expression is reduced in the hippocampus of rats exposed to Pb2+ during development. Brain Res Mol Brain Res. 66: 42-49.

Omelchenko IA, Nelson CS, Marino JL., Allen CN. (1996). The sensitivity of N-methyl-d-aspartate receptors to lead inhibition is dependent on the receptor subunit composition. J Pharmacol Exp Ther. 278: 15-20.

Omelchenko IA, Nelson CS, Allen CN. (1997) Lead inhibition of N-Methyl-D-aspartate receptors containing NR2A, NR2C and NR2D subunits. J Pharmacol Exp Ther. 282: 1458-1464.

Rumbaugh G, Vicini S. (1999) Distinct Synaptic and Extrasynaptic NMDA Receptors in Developing Cerebellar Granule Neurons. J Neurosc. 19: 10603-10610.

Traynelis S, Wollmuth LP, McBain CJ, Menniti FS, Vance KM, Ogden KK, Hansen KB, Yuan H, Myers SJ, Dingledine R. (2010) Glutamate receptor ion channels: structure, regulation, and function. Pharmacol Rev. 62: 405-496.

Zhang XY, Liu AP, Ruan DY, Liu J. (2002) Effect of developmental lead exposure on the expression of specific NMDA receptor subunit mRNAs in the hippocampus of neonatal rats by digoxigenin-labeled in situ hybridization histochemistry. Neurotox Teratol 24: 149-160.

Relationship: 213: Inhibition, NMDARs leads to Decreased, Calcium influx

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	adjacent	Moderate	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Moderate	

Key Event Relationship Description

The NMDA receptor is distinct in two ways: firstly, it is both ligand-gated and voltage-dependent and secondly, it requires co-activation by two ligands: glutamate and either D-serine or glycine.

NMDA receptor activation allows the influx of Ca2+ only when the receptor is occupied by L-glutamate or other agonists (and removal of Mg++ block) resulting in the postsynaptic membrane depolarization. Binding of antagonist to NMDA receptor decreases or eliminates Ca2+ influx and consequently dramatically decreases intracellular influx of Ca2+ levels (reviewed in Higley and Sabatini, 2012).

Evidence Supporting this KER

Biological Plausibility

The relationship between KE (NMDARs, Inhibition) and KE (Calcium influx, Decreased) is plausible as the function evaluation of NMDA receptors is commonly carried out by measurement of intracellular influx of Ca2+ upon NMDA receptor stimulation by agonist. Calcium imaging techniques have been extensively utilized to investigate the relationship between these two KEs. Almost 15% of the current through NMDA receptors is mediated by Ca2+ under physiological conditions (Higley and Sabatini, 2012).

It has been shown that less than five and, occasionally only a single NMDA receptor opens under physiological conditions, causing a total Ca2+ influx of about 6000 ions into a dendritic spine head reaching a concentration of ∼10 μM (Higley and Sabatini, 2012). However, the majority of the ions are rapidly eliminated by binding Ca2+ proteins, reaching ∼1 μM of free Ca2+ concentration (Higley and Sabatini, 2012).

In rat primary forebrain cultures, the intracellular Ca2+ increases after activation of the NMDA receptor and this increase is blocked when the cells are cultured under Ca2+ free conditions, demonstrating that the NMDA-evoked increase in intracellular Ca2+ derives from extracellular and not intracellular sources (Liu et al., 2013).

Neurons in brain slices from wild-type (GluRε2+/+) mice showed increase of intracellular Ca2+ in the presence of 100 μM NMDA that was completely inhibited after exposure to 100 mM APV. In contrast, the NMDA-mediated increase in Ca2+ was absent in brain slices from GluRε2−/− mice that do not possess any functional NMDA receptors in the developing neocortex (Okada et al., 2003).

Empirical Evidence

Pb2+: There are a few studies examining the effect of Pb2+ exposure on the changes in intracellular Ca2+. Incubation of rat synaptosomes with Pb2+ stimulates the activity of calmodulin reaching the higher effect at 30 μM, whereas higher concentrations of Pb2+ causes inhibition (Sandhir and Gill, 1994). Pb2+ exposure increases the activity of calmodulin by 45% in animal models. The IC50 values for inhibition of Ca2+ ATPase by Pb2+ has been found to be 13.34 and 16.69 μM in calmodulin-rich and calmodulin-depleted synaptic plasma membranes, respectively. Exposure of rats to Pb2+ has also inhibitory effect on Ca2+ ATPase activity, causing increase in intrasynaptosomal Ca2+ (Sandhir and Gill, 1994). In embryonic rat hippocampal neurons, exposure to 100 nM Pb2+ for periods from 1 hour to 2 days showes decrease of intracellular Ca2+ by a calmodulin-dependent mechanism (Ferguson et al., 2000).Calmodulin, as a calcium binding protein, has been strongly implicated in Pb toxicity. However, interactions between calcium and Pb on several binding sites suggest complex interactions (Kirberger, 2011).

There is evidence that Pb2+ exposure affects Ca2+ homeostasis causing alterations in the phosphorylation state of different kinases. For example, Pb2+ has been shown to interfere with MAPK signaling as it increases the phosphorylation of both ERK1/2 and p38(MAPK) (Cordova et al., 2004). However, the findings regarding calcium/calmodulin kinase II (CamKII) activity are not clear (Toscano and Guilarte, 2005). On one hand, Pb2+ has been found to cause reduction of CREB phosphorylation in the hippocampus of rats exposed during brain development (Toscano et al., 2003; Toscano et al., 2002). On the other hand, the levels of phosphorylation of CamKII have not been explored but only the mRNA expression levels have been studied in rat pups on PND 25 that received Pb2+ (180 and 375-ppm lead acetate in food for 30 days) and reached blood Pb2+ levels 5.8 to 10.3 μg/dl on PND 55 (Schneider et al., 2012). More specifically, CamKIIα gene expression has been found to be very sensitive to Pb2+ exposure in the frontal cortex but not in the hippocampus, whereas CamKIIβ gene expression in both brain structures remained unchanged (Schneider et al., 2012).

Acute Pb2+ (10μM) exposure impairs LTP (125.8% reduction of baseline) in CA1 region of hippocampus derived from Sprague-Dawley rats (15-18 PND) as it has been recorded by whole cell patch-clamp technique (Li et al., 2006). In the same study, through calcium imaging, it has been shown in the 10mM caffeine-perfused cultured hippocampal neurons that 10μM Pb2+ reduces intracellular Fluo-4 fluorescence ratio to 0.44 (Li et al., 2006).

Pb2+ chronically or acutely applied, significantly reduces LTP in CA1 region of hippocampus from Wistar or Sprague-Dawley rats (30 and 60 PND) (Carpenter et al., 2002). These animals were exposed to Pb2+ via the mother's drinking water either through gestation and lactation (upto day 21) (perinatal), only by lactation through the mother's drinking water and then in the pup's drinking water (post) or from gestation (pre and post). The concentrations of Pb2+ used in the drinking water were 0.1 and 0.2%. In CA1, LTP has been reduced at both ages and Pb2+ concentrations or duration of exposure. In CA3, there have been no differences with time of exposure, but there was a dramatic difference

in response as the age of animals increased. At 30 days LTP was significantly reduced, but at 60 days LTP was increased by about 30% (Carpenter et al., 2002). In the same brain structure and area (CA3) the effects of Pb2+ on LTP have been different in 30 PND and 60 PND rats after either acute perfusion of Pb2+ or from slices derived from rats after chronic developmental exposure to Pb2+, as inhibition of LTP has been recorded in 30 PND CA3, whereas potentiation has been measured in 60 PND CA3 with either exposure paradigm that have been attributed to possible involvement of protein kinase C (Hussain et al., 2000).

Stressor	**Experimental Model**	**Tested concentrations**	**Exposure route**	**Exposure duration**	**Inhibition of NMDAR (KE up) (measurements, quantitative if available)**	**Reduced Ca 2+ influx (KE down) (measurements, quantitative if available)**	**References**
Lead	CA1 pyramidal neurons derived from Sprague-Dawley rats (15-18 PND)	5-20 µM		25 min	By bath application of 5µM lead for 15 min prior to and 10 min after the tetanus, the LTP was induced to 151.4±3.5% of baseline. In the presence of 10µM lead, the LTP was reduced significantly to 125.8±2.9% of baseline. The reduction of 20µM lead to LTP was not significant with that of 10µM.	In the 10mM caffeine-perfused cultured hippocampal neurons, 10µM lead reduced intracellular Fluo-4 fluorescence ratio to 0.44±0.08	Li et al., 2006
Lead	CA1 region of hippocampus from Wistar or Sprague-Dawley rats	Two concentrations of lead were used in the drinking water 0.1 and 0.2%.	in utero and per os	Rats exposed to lead via the mother's drinking water either	In CA1, LTP is reduced at both ages, and there were no significant differences in the effects of the two lead		Carpenter et al., 2002

	(30 and 60 PND)			through gestation and lactation (to day 21) (perinatal), only by lactation through the mother's drinking water and then in the pup's drinking water until use (post) or from gestation until use (pre and post).	concentrations or with the duration of exposure. In CA3 there were no differences with time of exposure, but there was a dramatic difference in response as a function of age. At 30 days LTP was significantly reduced, but at 60 days LTP was increased by about 30%. As in the chronic exposure studies, lead reduced LTP in CA1 at both ages but reduced LTP in CA3 in 30-day animals while potentiating LTP in 60-day animals.		

Uncertainties and Inconsistencies

The structural diversity of NMDA subunits can influence the functionality of the receptors and their permeability to Ca2+. For example, NR2B subunits show higher affinity for glutamate binding and higher Ca2+ permeability (reviewed in Higley and Sabatini, 2012). But NMDA receptor subunit composition is not the only parameter that influences Ca2+ entrance in the cytosol. Membrane potential due to pore blockade by extracellular Mg2+ and receptor phosphorylation are two additional regulator of Ca2+ influx through NMDA receptors (reviewed in Higley and Sabatini, 2012).

Entrance of Ca2+ into neuronal cell can also happen through KA and AMPA receptors but to a smaller extent compared to NMDA receptors (reviewed in Higley and Sabatini, 2012).

However, recent findings suggest that AMPA receptors may also contribute to Ca2+ signalling during CNS development (reviewed in Cohen and Greenberg, 2008). Early in development cortical pyramidal neurons express calcium-permeable, GluR2 subunit–lacking AMPA receptors. During postnatal development these neurons undergo a switch in the subunit composition of AMPA receptors, expressing instead GluR2-containing, calcium-impermeable AMPA receptor suggesting that the main point entrance of Ca2+ at this developmental stage are NMDA receptors.

Furthermore, Ca2+ entry occurs through L- and H-type voltage-dependent Ca2+channels (L-VDCCs) (Perez-Reyes and Schneider, 1994; Berridge, 1998; Felix, 2005) that are encountered in neurons, suggesting that there are more possible entrance sites for Ca2+ to get into the cytosol rather than only through NMDA receptors.

Pb2+ is accumulated in the same mitochondrial compartment as Ca2+ and it has been linked to disruptions in intracellular calcium metabolism (Bressler and Goldstein, 1991). So, it can be that the reduced levels of Ca2+ after Pb2+ exposure may not be attributed to NMDA receptor inhibition but also to the ability of this heavy metal to compete with Ca2+. To make things more complicated, recent findings suggest that BDNF can also acutely elicit an increase in intracellular Ca2+ concentration, which is attributed not only to the influx of extracellular Ca2+ but also to Ca2+ mobilization from intracellular calcium stores (Numakawa et al., 2002; He et al., 2005). These findings derive from primary cultures of cortical neurons (E18 or 2-3 PND), where BDNF-evoked Ca2+ signals have not been altered neither by tetrodotoxin nor by a cocktail of glutamate receptor blockers (CNQX and APV), pointing out the importance of BDNF in Ca2+ homeostasis (Numakawa et al., 2002; He et al., 2005).

Domain of Applicability

Besides the above studies described in rodents, intracellular Ca2+ regulation has been studied at the neuromuscular junction of larval Drosophila exposed to 0, 100 μM or 250 μM Pb2+ (He et al., 2009).

References

Berridge MJ. (1998) Neuronal calcium signaling. Neuron 21: 13-26.

Bressler JP, Goldstein GW. (1991) Mechanisms of lead neurotoxicity. Biochem Pharmacol. 41: 479-484.

Carpenter DO, Hussain RJ, Berger DF, Lombardo JP, Park HY. (2002) Electrophysiologic and behavioral effects of perinatal and acute exposure of rats to lead and polychlorinated biphenyls. Environ Health Perspect. 110: 377-386.

Cohen S, Greenberg ME. (2008) Communication between the synapse and the nucleus in neuronal development, plasticity and disease. Annu Rev Cell Dev Biol. 24: 183-209.

Cordova FM, Rodrigues LS, Giocomelli MBO, Oliveira CS, Posser T, Dunkley PR, Leal RB. (2004) Lead stimulates ERK1/2 and p38MAPK phosphorylation in the hippocampus of immature rats. Brain Res. 998: 65-72.

Felix R. (2005) Molecular regulation of voltage-gated Ca2+ channels. J Recept Signal Transduct Res. 25: 57-71.

Ferguson C, Kern M, Audesirk G. (2000) Nanomolar concentrations of inorganic lead increase Ca2+ efflux and decrease intracellular free Ca2+ ion concentrations in cultured rat hippocampal neurons by a calmodulin-dependent mechanism. Neurotoxicology 21: 365-378.

Flora SJS, Flora G, Saxena G. (2006) Environmental occurrence, health effects and management of lead poisoning, in Lead: Chemistry, Analytical Aspects, Environmental Impacts and Health Effects (Cascas SB and Sordo J eds) Elsevier, Amsterdam, The Netherlands, pp 158-228.

He J, Gong H, Luo Q. (2005) BDNF acutely modulates synaptic transmission and calcium signalling in developing cortical neurons. Cell Physiol Biochem. 16: 69-76.

He T, Hirsch HV, Ruden DM, Lnenicka GA. (2009) Chronic lead exposure alters presynaptic calcium regulation and synaptic facilitation in Drosophila larvae. Neurotoxicology 30: 777-784.

Higley MJ, Sabatini BL. (2012) Calcium signalling in dendritic spines. Cold Spring Harb Perspect Biol 4: a005686.

Hussain RJ, Parsons PJ, Carpenter DO. (2000) Effects of lead on long-term potentiation in hippocampal CA3 vary with age. Brain Res Dev Brain Res. 121: 243-252.

Kirberger, M. (2011) Defining a Molecular Mechanism for Lead toxicity via Calcium-Binding Proteins. Chemistry Dissertation. Georgia State University. ScholarWorks@Georgia State University.

Li XM, Gu Y, She JQ, Zhu DM, Niu ZD, Wang M, Chen JT, Sun LG, Ruan DY. (2006) Lead inhibited N-methyl-D-aspartate receptor-independent long-term potentiation involved ryanodine-sensitive calcium stores in rat hippocampal area CA1. Neuroscience. 139: 463-473.

Liu F, Patterson TA, Sadovova N, Zhang X, Liu S, Zou X, Hanig JP, Paule MG, Slikker W Jr, Wang C. (2013) Ketamine-induced neuronal damage and altered N-methyl-D-aspartate receptor function in rat primary forebrain culture. Toxicol Sci. 131: 548-557.

Numakawa T, Yamagishi S, Adachi N, Matsumoto T, Yokomaku D, Yamada M, Hatanaka H (2002) Brain-derived neurotrophic factor-induced potentiation of Ca2+ oscillations in developing cortical neurons. J Biol Chem. 277: 6520-6529.

Okada H, Miyakawa N, Mori H, Mishina M, Miyamoto Y, Hisatsune T. (2003) NMDA receptors in cortical development are essential for the generation of coordinated increases in [Ca2+](i) in "neuronal domains". Cereb Cortex. 13 :749-757.

Perez-Reyes E, Schneider T. (1994) Calcium channels: Structure, function, and classification. Drug Dev Res. 33: 295–318.

Sandhir R, Gill KD. (1994) Alterations in calcium homeostasis on lead exposure in rat synaptosomes. Mol Cell Biochem. 131: 25-33.

Schneider JS, Mettil W, Anderson DW. (2012) Differential Effect of Postnatal Lead Exposure on Gene Expression in the Hippocampus and Frontal Cortex. J Mol Neurosci. 47: 76-88.

Sinner B, Friedrich O, Zink W, Martin E, Fink RH, et al. (2005) Ketamine stereoselectively inhibits spontaneous Ca2+-oscillations in cultured hippocampal neurons. Anesthesia and analgesia 100: 1660-1666.

Toscano CD, Guilarte TR. (2005) Lead neurotoxicity: From exposure to molecular effects. Brain Res Rev. 49: 529-555.

Toscano CD, Hashemzadeh-Gargari H, McGlothan JL, Guilarte TR. (2002) Developmental Pb2+ exposure alters NMDAR subtypes and reduces CREB phosphorylation in the rat brain. Dev Brain Res. 139: 217-226.

Toscano CD, McGlothan JL, Guilarte TR. (2003) Lead exposure alters cyclic-AMP response element binding protein phosphorylation and binding activity in the developing rat brain. Dev Brain Res. 145: 219-228.

Relationship: 347: Decreased, Calcium influx leads to BDNF, Reduced

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	non-adjacent	Low	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Low	

Key Event Relationship Description

Mainly, NMDA receptor activation initiates Ca2+-dependent signaling events that regulate the expression of genes involved in regulation of neuronal function including *bdnf* (reviewed in Cohen and Greenberg, 2008). Inhibition of NMDA receptors results in low levels of Ca2+ and decreased transcription of BDNF and consequently to low level of BDNF protein production and release.

Evidence Supporting this KER

Biological Plausibility

BDNF transcription is induced by Ca2+ entering through either L type voltage gated calcium channel (L-VGCC) (Tao et al., 1998) or NMDA receptor (Tabuchi et al., 2000; Zheng et al., 2011) that can last up to 6 h. BDNF IV that is the most studied among its different exons has been shown to bind three Ca2+ elements within the regulatory region (reviewed in Zheng et al., 2012). One of these Ca2+ elements binds to CREB facilitating transcription. However, more transcription factors rather than only CREB are implicated in the transcription process of BDNF such as NFAT (nuclear factor of activated T cell), MEF2 (myocyte enhancer factor 2) and NFκB (nuclear factor κB) (reviewed in Zheng et al., 2012). The activation of the relevant transcription factor is triggered by the initial activation of CaM kinase, cAMP/PKA and Ras/ERK1/2 pathways mediated by the elevated intracellular Ca2+. Interestingly, inhibitory studies targeting different elements of these pathways report reduction at mRNA BDNF levels (reviewed in Zheng et al., 2012).

In particular, exon IV BDNF mRNA transcription is regulated by a transcriptional silencer, methyl-CpG binding protein 2 (MeCP2), demonstrating that epigenetic alterations can also regulate BDNF transcription. Increase of intracellular Ca2+ levels phosphorylates MeCP2, which inactivates its repressor function and permits the transcription of BDNF exon IV (Chen et al., 2003; Greer and Greenberg, 2008; Tao et al., 2009; Zhou et al., 2006). Indeed, NMDA receptor activation has been shown to upregulate BDNF transcripts containing exon IV not only via Ca2+-dependent CREB but also through Ca2+ activation of MeCP2 transcription (Metsis et al., 1993; Shieh et al., 1998, Tao et al., 1998; Tabuchi et al., 2000; Chen et al., 2003; Jiang et al., 2005; Zheng et al., 2011), whereas NMDAR antagonists

decrease BDNF exon IV expression (Zafra et al., 1991; Stansfield et al., 2012). Furthermore, BDNF mRNA is also targeted in different locations within the cell during the process of translation, depending on the promoter used (reviewed in Tongiorgi et al., 2006).

Interestingly, synaptic and extra-synaptic NMDARs have opposite effects on CREB: indeed calcium entry through synaptic NMDAR induced CREB activity and BDNF gene expression. In contrast, calcium entry through extra-synaptic NMDAR activates a general and dominant CREB shut-off pathway that blocked induction of BDNF expression (Hardingham et al., 2002).

Empirical Evidence

There is no direct evidence linking reduced levels of Ca2+ to decreased BDNF levels as they have not been ever measured both in the same study after exposure to stressors. However, there are findings that strongly link the different elements of Ca2+-dependent signalling events to transcription of BDNF.

Pb2+: Pb2+ decreases the ratio of phosphorylated versus total MeCP2 and consequently MeCP2 maintains its repressor function and prevents BDNF exon IV transcription (Stansfield et al., 2012). MeCP2 gene expression in the frontal cortex is very sensitive to Pb2+ exposure while in the hippocampus, the same gene is affected only at the higher exposure group in rat pups with blood Pb2+ levels 5.8 to 10.3 μg/dl on PND 55 (Schneider et al., 2012). In two different *in vivo* studies from the same research group, the use of doses of Pb2+ that result in learning and LTP deficits in rats causes decrease in phosphorylation of CREB in cerebral cortex at 14 PND and the same reduction in phosphorylation state of CREB in both cortex and hippocampus at PND 50 (Toscano et al., 2002; 2003). Interestingly, under similar experimental conditions no alteration at the phosphorylation state of CAMKII has been recorded (Toscano et al., 2005). In primary hippocampal neurons exposed to 1 μM Pb2+ for 5 days during the period of synaptogenesis (DIV7–DIV12), both the cellular and extracellular proBDNF protein levels of mBDNF decrease with the latter to smaller extend (Neal et al., 2010). In the same *in vitro* model, Pb2+ also decreases dendritic proBDNF protein levels throughout the length of the dendrites and causes impairment of BDNF vesicle transport to sites of release in dendritic spines (Stansfield et al., 2012). Furthermore, Pb2+ treatment resulted in a specific reduction of Bdnf exon IV and IX mRNA transcripts causing no alteration in the expression of exons I and II (Stansfield et al., 2012). Rat pups on PND 25 exposed to Pb2+ (180 and 375-ppm lead acetate in food for 30 days) demonstrated blood Pb2+ levels 5.8 to 10.3 μg/dl on PND 55 and show no change at gene levels of BDNF (Schneider et al., 2012). In mouse embryonic stem cells (ESCs), Bdnf exon IV has been found to be down-regulated in cells treated with 0.1 μM Pb, whereas Bdnf exon IX has been found up-regulated (Sánchez-Martín et al., 2013).

Uncertainties and Inconsistencies

In a gene expression study, where gene analysis has been performed in the hippocampus derived from male or female rats fed with 1500 ppm Pb2+-containing chow for 30 days beginning at weaning, two molecular networks have been identified that were different between male and female treated rats. In these networks, CREB was the highly connected node, common for both networks (Schneider et al., 2011). However, no change has been reported in the expression of bdnf gene neither in male nor in female rats treated with Pb2+ (Schneider et al., 2011).

References

Chen WG, Chang Q, Lin Y, Meissner A, West AE, Griffith EC, Jaenisch R, Greenberg ME. (2003) Derepression of BDNF transcription involves calcium-dependent phosphorylation of MeCP2. Science. 302: 885-889.

Cohen S, Greenberg ME. (2008) Communication between the synapse and the nucleus in neuronal development, plasticity and disease. Annu Rev Cell Dev Biol. 24: 183-209.

Greer PL, Greenberg ME. (2008) From synapse to nucleus: Calcium-dependent gene transcription in the control of synapse development and function. Neuron 59: 846-860.

Hardingham GE, Bading H. 2002. Coupling of extrasynaptic NMDA receptors to a CREB shut-off pathway is developmentally regulated. Biochim Biophys Acta 1600(1-2): 148-153.

Heaton MB, Mitchell JJ, Paiva M. (1999) Ethanol-induced alterations in neurotrophin expression in developing cerebellum: relationship to periods of temporal susceptibility. Alcohol Clin Exp Res. 23: 1637-1642.

Jiang X, Tian F, Mearow K, Okagaki P, Lipsky RH, Marini AM. (2005) The excitoprotective effect of N-methyl-D-aspartate receptors is mediated by a brain-derived neurotrophic factor autocrine loop in cultured hippocampal neurons. J Neurochem. 94: 713-722.

Metsis M, Timmusk T, Arenas E, Persson H. (1993) Differential usage of multiple brain-derived neurotrophic factor promoters in the rat brain following neuronal activation. Proc Natl Acad. Sci USA. 90: 8802-8806.

Neal AP, Stansfield KH, Worley PF, Thompson RE, Guilarte TR. (2010) Lead exposure during synaptogenesis alters vesicular proteins and impairs vesicular release: Potential role of NMDA receptor-dependent BDNF signaling. Toxicol Sci. 116: 249-263.

Sánchez-Martín FJ, Fan Y, Lindquist DM, Xia Y, Puga A. (2013) Lead Induces Similar Gene Expression Changes in Brains of Gestationally Exposed Adult Mice and in Neurons Differentiated from Mouse Embryonic Stem Cells. PLoS One 8: e80558.

Schneider JS, Anderson DW, Sonnenahalli H, Vadigepalli R. (2011) Sex-based differences in gene expression in hippocampus following postnatal lead exposure. Toxicol Appl Pharmacol. 256: 179-190.

Schneider JS, Mettil W, Anderson DW. (2012). Differential Effect of Postnatal Lead Exposure on Gene Expression in the Hippocampus and Frontal Cortex. J Mol Neurosci. 47: 76-88.

Shieh PB, Hu SC, Bobb K, Timmusk T, Ghosh A. (1998) Identification of a signaling pathway involved in calcium regulation of BDNF expression. Neuron 20: 727–740.

Stansfield KH, Pilsner JR, Lu Q, Wright RO, Guilarte TR. (2012) Dysregulation of BDNF-TrkB signaling in developing hippocampal neurons by Pb(2+): implications for an environmental basis of neurodevelopmental disorders. Toxicol Sci. 127: 277-295.

Tabuchi A, Nakaoka R, Amano K, Yukimine M, Andoh T, Kuraishi Y and Tsuda M. (2000) Differential activation of brain-derived neurotrophic factor gene promoters I and III by Ca2+ signals evoked via L-type voltage-dependent and N-methyl-D-aspartate receptor Ca2+ channels. J Biol Chem. 275: 17269-17275.Tao X, Finkbeiner S, Arnold DB, Shaywitz AJ, Greenberg ME. (1998) Ca2+ influx regulates BDNF transcription by a CREB family transcription factor-dependent mechanism. Neuron 20: 709-726.

Tao J, Hu K, Chang Q, Wu H, Sherman NE, Martinowich K, Klose RJ, Schanen C, Jaenisch R, Wang W, et al. (2009) Phosphorylation of MeCP2 at Serine 80 regulates its chromatin association and neurological function. Proc Natl Acad Sci USA. 106: 4882-4887.

Tongiorgi E, Domenici L, Simonato M. (2006) What is the biological significance of BDNF mRNA targeting in the dendrites? Clues from epilepsy and cortical development. Mol Neurobiol. 33: 17-32.

Toscano CD, Hashemzadeh-Gargari H, McGlothan JL, Guilarte TR. (2002) Developmental Pb2+ exposure alters NMDAR subtypes and reduces CREB phosphorylation in the rat brain. Brain Res Dev Brain Res. 139: 217-226.

Toscano CD, McGlothan JL, Guilarte TR. (2003) Lead exposure alters cyclic-AMP response element binding protein phosphorylation and binding activity in the developing rat brain. Brain Res. Dev. Brain Res. 145: 219-228.

Toscano CD, O'Callaghan JP, Guilarte TR. (2005) Calcium/calmodulin-dependent protein kinase II activity and expression are altered in the hippocampus of Pb2+-exposed rats. Brain Res. 1044: 51–58.

Zafra F, Castrén E, Thoenen H, Lindholm D. (1991) Interplay between glutamate and gamma-aminobutyric acid transmitter systems in the physiological regulation of brain-derived neurotrophic factor and nerve growth factor synthesis in hippocampal neurons. Proc Natl Acad Sci U S A. 88: 10037-10041.

Zheng F, Zhou X, Luo Y, Xiao H, Wayman G, Wang H. (2011) Regulation of brain-derived neurotrophic factor exon IV transcription through calcium responsive elements in cortical neurons. PLoS One 6: e28441.

Zheng F, Zhou X, Moon C, Wang H. (2012) Regulation of brain-derived neurotrophic factor expression in neurons. In J Pathophysiol Pharmacol 4: 188-200.

Zhou Z, Hong EJ, Cohen S, Zhao WN, Ho HY, Schmidt L, Chen WG, Lin Y, Savner E, Griffith EC, et al. (2006) Brain-specific phosphorylation of MeCP2 regulates activity-dependent Bdnf transcription, dendritic growth, and spine maturation. Neuron 52: 255-269.

Relationship: 353: BDNF, Reduced leads to N/A, Cell injury/death

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development induces impairment of learning and memory abilities	non-adjacent	Low	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Low	

Evidence Supporting Applicability of this Relationship

The survival and antiapoptotic role of BDNF has been investigated not only in rodents but also in developing chicken neurons (Hallbook et al., 1995; Frade et al., 1997; Reinprecht et al., 1998). In invertebrates, only recently a protein with possible neurotrophic role has been identified but its influence and function in neuronal cell death of developing neurons has not been investigated yet (Zhu et al., 2008).

Key Event Relationship Description

BDNF influences the apoptosis occurring in developing neurons through two distinct mechanisms (Bernd, 2008). mBDNF can trigger prosurvival signaling after binding to TrkB receptor through inactivation of components of the cell death machinery and also through activation of the transcription factor cAMP-response element binding protein (CREB), which drives expression of the pro-survival gene Bcl-2 (West et al., 2001). On the other hand, proBDNF binds to the p75 neurotrophin receptor (p75NTR) and activates RhoA that regulates actin cytoskeleton polymerization resulting in apoptosis (Lee et al., 2001; Miller and Kaplan, 2001; Murray and Holmes, 2011). It is proved that reduced levels of BDNF can severely interfere with the survival of neurons in different brain regions, leading to cell death (Lee et al., 2001; Miller and Kaplan, 2001; Murray and Holmes, 2011).

Evidence Supporting this KER

Biological Plausibility

BDNF mRNA levels dramatically increase between embryonic days 11 to 13 during rat development, playing important role in neuronal differentiation and survival (reviewed in Murray and Holmes, 2011). The latter has been supported by transgenic experiments where BNDF−/− mice demonstrated a dramatic increase in cell death among developing granule cells leading to impaired development of the layers of the cerebellar cortex (Schwartz et al., 1997). BDNF has also been shown to provide neuroprotection after hypoxic-ischemic brain injury in neonates (P7) but not in older (P21) animals (Cheng et al., 1997; Han and

Holtzman, 2000). The neuroprotective role of BDNF has been further supported by the observed correlation between elevated BDNF protein levels and resistance to ischemic damage in hippocampus *in vivo* (Kokaia et al., 1996) and K+ rich medium-induced apoptosis *in vitro* (Kubo et al., 1995).

Empirical Evidence

Several *in vitro* and *in vivo* studies on cortical neurons have demonstrated that the survival of developing neurons is closely related with the activation of the NMDA receptors and subsequent BDNF synthesis/release that fully support the BDNF neurotrophic theory (Ikonomidou et al., 1999; Yoon et al., 2003; Hansen et al., 2004).

Pb2+: Neonatal mice exposed to Pb2+ (350 mg/kg lead twice every 4 h) and sacrificed after 8-24 h show increased apoptotic neurodegeneration above that seen in normal controls. This effect has been recorded only in animals treated with Pb2+ at PND 7, but not at PND 14 (Dribben et al., 2011), confirming the importance of the time of exposure during development in order for Pb2+ to induce apoptosis. Two to four weeks old rats treated for 7 days with 15 mg/kg daily dose of lead acetate show increased apoptosis in hippocampus (Sharifi et al., 2002). In rats (30 PND), it has also been shown that Pb2+ (2, 20 and 200 mg/kg/d) can induce apoptosis (Liu et al., 2010). However, in contrast to the first two *in vivo* studies, the animals in this experimental approach were old enough to evaluate the most sensitive window of vulnerability of developing neurons to Pb2+ exposure (Liu et al., 2010), confirming that only Pb2+ treatment during synaptogenesis can lead to neuronal cell apoptosis. *In vitro* evidence of apoptosis induced by Pb2+ also derive from PC12 cells exposed to Pb2+ (0.1, 1, 10 μM) that have shown increased activation of caspase-3 (Xu et al., 2006). Besides PC12 cells (Xu et al., 2006; Sharifi and Mousavi, 2008), lead-induced apoptosis has also been studied in cultured rat cerebellar neurons (Oberto et al., 1996), hippocampal neurons (Niu et al., 2002) and retinal rod cells (He et al., 2000). No significant increase in LDH release was found in neuro-spheres derived from neural stem cells (NSCs) originating from E15 rat cortex (CX), striatum (ST) or ventral mesencephalon (VM) after assessing at 24 h intervals from day 1 through day 7 after addition of lead acetate (0.1–10 μM) (Huang and Schneider, 2004). However, LDH release was increased 1 day after addition of 100 μM lead acetate (1.6-2.1 fold depending on the brain region) and 3 days after addition of 50 μM lead acetate to the culture medium (1.3-1.5 fold depending on the brain region). No significant cell loss was observed in cultures exposed to 0.1–10 μM lead acetate for 7 days after staining with Hoechst 33342. In contrast, significant cell loss was observed 7 days after exposure to 50 μM (35-50% depending on brain region) or 100 μM lead acetate (60-75% depending on brain region) (Huang and Schneider, 2004). In primary rat hippocampal neurons exposed to 1 μM Pb2+ for 5 days during the period of synaptogenesis (DIV7–DIV12), decreased cellular proBDNF protein (40% compared to control) and extracellular levels of mBDNF (25% compared to control) have been recorded (Neal et al., 2010). Significant reductions specifically in dendritic proBDNF protein levels throughout the length of the dendrites have also been described by Stansfield et al. (2012) after exposure to the same concentration of Pb2+ using this *in vitro* model. In an *in vivo* study, mice at PND 7 with mean Pb2+ blood levels of 8.10 μg/mL have shown increased apoptosis in the cortex, hippocampus, caudate-putamen, and thalamus compared to controls with F (1,14) = 19.5, 8.40, 4.15, 4.53, respectively (Dribben et al., 2011). These Pb2+ levels in blood (Dribben et al., 2011) were a bit higher than the levels determined in Guilarte et al. 2003 (3.90 μg/dl) that served as the base to calculate *in vitro* doses in Neal et al. 2010 and Stansfield et al. 2012.

Uncertainties and Inconsistencies

Pb2+: A number of studies demonstrate that deletion of BDNF does not lead to significant apoptotic cell death of neurons in the developing CNS (reviewed in Dekkers et al., 2013). In an *in vivo* Pb2+ exposure study, where female rats received 1,500 ppm prior, during breeding and lactation shows no changes at mRNA levels of BDNF in different hippocampus section derived from their pups (Guilarte et al., 2003). Regarding Pb2+, the pre- and neonatal exposure of rats to Pb2+ (Pb2+ blood levels below 10 μg/dL) show a decreased number of hippocampus neurons but no morphological or molecular features of severe apoptosis or necrosis have been detected in tested brains (Baranowska-Bosiacka et al., 2013). In contrast to the lack of apoptotic signs, reduced levels of BDNF concentration (pg/mg protein) of BDNF in brain homogenates has been recorded in forebrain cortex (39%) and hippocampus (29%) (Baranowska-Bosiacka et al., 2013). Pregnant rats have been exposed to lead acetate (0.2% in the drinking water) after giving birth until PND 20. At PND 20, blood Pb2+ levels in pups reached at 80 μg/dl. In these animals, the gene expression in different brain regions has been assessed and demonstrated that hippocampus is most sensitive with alterations beginning at PND 12 when caspase 3 mRNA increases after Pb2+ exposure (Chao et al., 2007). However, bcl-x and BDNF mRNA in the hippocampus have been significantly increased after caspase 3 increase, suggesting that the apoptotic signal activates a compensatory response by increasing survival factors like BDNF and that the temporality suggested in this AOP may not be accurate (Chao et al., 2007).

Some of the reported "inconsistencies" may be due to the lack of sufficient details in the reporting since publications vary in what they measure. Some of the referenced studies look at BDNF transcripts, others look at BDNF protein. BDNF processing is highly complex and different mRNA transcripts are known to be implicated in different cellular function.

Several studies addressing apoptosis mainly in the developing cerebral cortex have shown that more mechanism besides neurotrophic factors may be involved. Cytokines, as well as neurotransmitters can potentially activate a number of intracellular proteins that execute cell death (Henderson, 1996; Kroemer et al., 2009), meaning that further branches to this AOP might be added in the future.

References

Baranowska-Bosiacka, Strużyńska L, Gutowska I, Machalińska A, Kolasa A, Kłos P, Czapski GA, Kurzawski M, Prokopowicz A, Marchlewicz M, Safranow K, Machaliński B, Wiszniewska B, Chlubek D. (2013) Perinatal exposure to lead induces morphological, ultrastructural and molecular alterations in the hippocampus. Toxicology. 303: 187-200.

Bernd P. (2008) The role of neurotrophins during early development. Gene Expr. 14: 241-250.

Chao SL, Moss JM, Harry GJ. (2007) Lead-induced Alterations of Apoptosis and Neurotrophic Factor mRNA in the Developing Rat Cortex, Hippocampus, and Cerebellum. J Biochem Mol Toxicol. 21: 265-272.

Cheng Y, Gidday JM, Yan Q et al (1997) Marked age-dependent neuroprotection by brain-derived neurotrophic factor against neonatal hypoxic-ischemic brain injury. Ann Neurol 41: 521-529.

Dekkers MP, Nikoletopoulou V, Barde YA. (2013) Cell biology in neuroscience: Death of developing neurons: new insights and implications for connectivity. J Cell Biol. 203: 385-393.

Dikranian K, Ishimaru MJ, Tenkova T, Labruyere J, Qin YQ, Ikonomidou C, Olney JW. (2001) Apoptosis in the *in vivo* mammalian forebrain. Neurobiol Dis. 8: 359-379.

Dribben WH, Creeley CE, Farber N. (2011) Low-level lead exposure triggers neuronal apoptosis in the developing mouse brain. Neurotoxicol Teratol. 33: 473-480.

Farber NB, Creeley CE, Olney JW. (2010) Alcohol-induced neuroapoptosis in the fetal macaque brain. Neurobiol Dis. 40:200-206.

Frade JM, Bovolenta P, Martínez-Morales JR, Arribas A, Barbas JA, Rodríguez-Tébar A. (1997) Control of early cell death by BDNF in the chick retina. Development. 124: 3313-3320.

Guilarte TR, Toscano CD, McGlothan JL, Weaver SA. (2003) Environmental enrichment reverses cognitive and molecular deficits induced by developmental lead exposure. Ann Neurol. 53: 50-56.

Hallbook F, Bäckström A, Kullander K, Kylberg A, Williams R, Ebendal T (1995). Neurotrophins and their receptors in chicken neuronal development. Int J Dev Biol. 39: 855-868.

Han BH, Holtzman DM (2000) BDNF protects the neonatal brain from hypoxic-ischemic injury *in vivo* via the ERK pathway. J Neurosci. 20: 5775-57811.

Hansen HH, Briem T, Dzietko M, Sifringer M, Voss A, Rzeski W, Zdzisinska B, Thor F, Heumann R, Stepulak A, Bittigau P, Ikonomidou C. (2004). Mechanisms leading to disseminated apoptosis following NMDA receptor blockade in the developing rat brain. Neurobiol Dis. 16: 440-453.

He L, Poblenz AT, Medrano CJ, Fox DA. Lead and calcium produce rod photoreceptor cell apoptosis by opening the mitochondrial permeability transition pore. J Biol Chem. 2000 Apr 21;275(16):12175-84.

Henderson CE. (1996). Programmed cell death in the developing nervous system. Neuron 17: 579-585.

Huang F, Schneider JS. (2004) Effects of lead exposure on proliferation and differentiation of neural stem cells derived from different regions of embryonic rat brain. Neurotoxicology 25: 1001–1012.

Ikonomidou C, Bosch F, Miksa M, Bittigau P, Vöckler J, Dikranian K, Tenkova TI, Stefovska V, Turski L, Olney JW. (1999) Blockade of NMDA receptors and apoptotic neurodegeneration in the developing brain. Science 283: 70-74.

Kokaia Z, Nawa H, Uchino H, Elmer E, Kokaia M, Carnahan J, Smith ML, Siesjo BK & Lindvall O. (1996) Regional brain-derived neurotrophic factor mRNA and protein levels following transient forebrain ischemia in the rat. Brain Res Mol Brain Res. 38: 139-144.

Kroemer G, Galluzzi L, Vandenabeele P, Abrams J, Alnemri ES, Baehrecke EH, Blagosklonny MV, El-Deiry WS., Golstein P, Green DR, Hengartner M, Knight RA, Kumar S, Lipton SA, Malorni W, Nuñez G, Peter ME, Tschopp J, Yuan J, Piacentini M, Zhivotovsky B, Melino G. Nomenclature Committee on Cell Death (2009). Classification of cell death: recommendations of the Nomenclature Committee on Cell Death 2009. Cell Death Differ. 16: 3-11.

Kubo T, Nonomura T, Enokido Y, Hatanaka H. (1995) Brain-derived neurotrophic factor (BDNF) can prevent apoptosis of rat cerebellar granule neurons in culture. Brain Res Dev Brain Res. 85: 249-258.

Lee R, Kermani P, Teng KK, Hempstead BL. (2001) Regulation of cell survival by secreted proneurotrophins. Science 294: 1945-1948.

Liu J, Han D, Li Y, Zheng L, Gu C, Piao Z, Au WW, Xu X, Huo X. (2010) Lead affects apoptosis and related gene XIAP and Smac expression in the hippocampus of developing rats. Neurochem Res. 35: 473-479.

Miller FD, Kaplan DR. (2001) Neurotrophin signalling pathways regulating neuronal apoptosis. Cell Mol Life Sci. 58: 1045-1053.

Murray PS, Holmes PV. (2011) An Overview of Brain-Derived Neurotrophic Factor and Implications for Excitotoxic Vulnerability in the Hippocampus nternational. J Pept. Volume 2011 (2011), Article ID 654085, 12 pages.

Neal AP, Stansfield KH, Worley PF, Thompson RE, Guilarte TR. (2010) Lead exposure during synaptogenesis alters vesicular proteins and impairs vesicular release: Potential role of NMDA receptor-dependent BDNF signaling. Toxicol Sci. 116: 249-263.

Niu Y, Zhang R, Cheng Y, Sun X, Tian J. (2002) Effect of lead acetate on the apoptosis and the expression of bcl-2 and bax genes in rat brain cells. Zhonghua Yu Fang Yi Xue Za Zhi. 36: 30-33.

Oberto A, Marks N, Evans HL, Guidotti A. (1996) Lead (Pb + 2) promotes apoptosis in newborn rat cerebellar neurons: pathological implications. J Pharmacol Exp Ther. 279: 435-442.

Reinprecht K, Hutter-Paier B, Crailsheim K, Windisch M. (1998) Influence of BDNF and FCS on viability and programmed cell death (PCD) of developing cortical chicken neurons *in vitro*. J Neural Transm Suppl. 53: 373-384.

Schwartz PM, Borghesani PR, Levy RL, Pomeroy SL, Segal RA. (1997) Abnormal cerebellar development and foliation in BDNF(-/-) mice reveals a role for neurotrophins in CNS patterning. Neuron 19: 269-281.

Sharifi AM, Baniasadi S, Jorjani M, Rahimi F, Bakhshayesh M. (2002) Investigation of acute lead poisoning on apoptosis in rat hippocampus *in vivo*. Neurosci Lett. 329: 45-48.

Sharifi AM, Mousavi SH. (2008) Studying the effects of lead on DNA fragmentation and proapoptotic bax and antiapoptotic bcl-2 protein expression in PC12 cells. Toxicol. Mech. Methods 18: 75-79.

Stansfield KH, Pilsner JR, Lu Q, Wright RO, Guilarte TR. (2012) Dysregulation of BDNF-TrkB signaling in developing hippocampal neurons by Pb(2+): implications for an environmental basis of neurodevelopmental disorders. Toxicol Sci. 127: 277-295.

West AE, Chen WG, Dalva MB, Dolmetsch RE, Kornhauser JM, Shaywitz AJ, Takasu MA, Tao X, Greenberg ME. (2001) Calcium regulation of neuronal gene expression. Proc Natl Acad Sci U S A. 98: 11024-11031.

Xu J, Ji LD, Xu LH. (2006) Lead-induced apoptosis in PC 12 cells: involvement of p53, Bcl-2 family and caspase-3. Toxicol Lett. 166: 160-167.

Yoon WJ, Won SJ, Ryu BR, Gwag BJ. (2003). Blockade of ionotropic glutamate receptors produces neuronal apoptosis through the Bax- cytochrome C-caspase pathway: the causative role of Ca2+deficiency. J Neurochem. 85: 525-533.

Zhu B, Pennack JA, McQuilton P, Forero MG, Mizuguchi K, Sutcliffe B, Gu CJ, Fenton JC, Hidalgo A. (2008) Drosophila neurotrophins reveal a common mechanism for nervous system formation. PLoS Biol. 18;6(11):e284.

Relationship: 365: N/A, Cell injury/death leads to N/A, Neuroinflammation

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	non-adjacent	Low	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Moderate	
Binding of electrophilic chemicals to SH(thiol)-group of proteins and /or to seleno-proteins during brain development leads to impairment of learning and memory	adjacent		

Key Event Relationship Description

The pioneering work of Kreutzberg and coworkers (1995, 1996) has shown that neuronal injury leads to neuroinflammation, with microglia and astrocyte reactivities. Several chemokines and chemokines receptors (fraktalkine, CD200) control the neuron-microglia interactions, and a loss of this control can trigger microglial reactivity (Blank and Prinz, 2013; Chapman et al., 2000; Streit et al., 2001). Upon injury causing neuronal death (mainly necrotic), signals termed Damage-Associated Molecular Patterns (DAMPs) are released by damaged neurons and promote microglial reactivity (Marin-Teva et al., 2011; Katsumoto et al., 2014). Toll-like receptors (TLRs) are pattern-recognition receptors that recognise specific pathogen- and danger-associated molecular signatures (PAMPs and DAMPs) and subsequently initiate inflammatory and immune responses. Microglial cells express TLRs, mainly TLR-2, which can detect neuronal cell death (for review, see Hayward and Lee, 2014). TLR-2 functions as a master sentry receptor to detect neuronal death and tissue damage in many different neurological conditions including nerve trans-section injury, traumatic brain injury and hippocampal excitotoxicity (Hayward and Lee, 2014). Astrocytes, the other cellular mediator of neuroinflammation (Ranshoff and Brown, 2012), are also able to sense tissue injury via TLR-3 (Farina et al., 2007; Rossi, 2015).

Evidence Supporting this KER

Biological Plausibility

It is widely accepted that cell/neuronal injury and death lead to neuroinflammation (microglial and astrocyte reactivities) in adult brain. In the developing brain, neuroinflammation was observed after neurodegeneration induced by excitotoxic lesions (Acarin et al., 1997; Dommergues et al., 2003) or after ethanol exposure (Tiwari et al., 2012; Ahmad et al., 2016). It is important to note that physiological activation of microglial cells is observed during normal brain development for removal of apoptotic debris (Ashwell 1990, 1991). But exposure to toxicant (ethanol), excitotoxic insults (kainic acid) or traumatic brain injury during development can also induce apoptosis in hippocampus

and cerebral cortex, as measured either by TUNEL, BID or caspase 3 upregulation associated to an inflammatory response, as evidenced by increased level of pro-inflammatory cytokines IL-1b, TNF-a, of NO, of p65 NF-kB or of the marker of astrogliosis, glial fibrillary acidic protein (GFAP), suggesting that, during brain development, neuroinflammation can also be triggerred by apoptosis induced by several types of insult (Tiwari and Chopra, 2012; Baratz et al., 2015; Mesuret et al., 2014).

Empirical Evidence

Pb

In 3D cultures prepared from fetal rat brain cells exposed to Pb (10^{-6} - 10^{-4} M for 10 days), Pb-induced neuronal death was evidenced by a decrease of cholinergic and GABAergic markers associated to a decrease in protein content, and was accompanied by microglial and astrocyte reactivities (Zurich et al., 2002). These effects were more pronounced in immature than in differentiated cultures (Zurich et al., 2002). In adult rats, exposure to 100 ppm of Pb for 8 weeks caused neuronal death, evidenced by an increase in apoptosis (TUNEL) that was associated with microglial reactivity and an increase in IL-1b, TNF-a and i-NOS expression (Liu et al., 2012). Acute exposure to Pb (25 mg/kg, ip, for 3 days) increased GFAP and glutamate synthetase expression with impaiment of glutamate uptake and probable neuronal injury (Struzunska, 2000; Struzunska et al., 2001).

Domoic acid

- Astrogliosis is one of the histopathological findings revealed by the assessment of brains derived from patients diagnosed with Amnesic Shellfish Poisoning (ASP) (reviewed in Pulido, 2008). In a reference study, where the brain of a patient after acute DomA intoxication has been examined in great detail gliosis has been detected in the overlying cortex, dorsal and ventral septal nuclei, the secondary olfactory areas and the nucleus accumbens (Cendes et al., 1995). Reactive astrogliosis has also been confirmed in the sixth cortical layer and subjacent white matter in the orbital and lateral basal areas, the first and second temporal gyri, the fusiform gyrus, the parietal parasagittal cortex, and the insula (Cendes et al., 1995).
- Adult rats have been assessed seven days after the administration of DomA (2.25 mg/kg i.p.) and revealed astrocytosis identified by glial fibrillary acidic protein (GFAP)-immunostaining and activation of microglia by GSI-B4 histochemistry (Appel et al., 1997). More investigators have suggested that DomA can activate microglia (Ananth et al., 2001; Chandrasekaran et al., 2004).
- DomA treatment (2 mg/kg once a day for 3 weeks) in mice significantly stimulates the expression of inflammatory mediators, including IL-1β (1.7 fold increase), TNF-α (2 fold increase), GFAP (1.4 fold increase), Cox-2 (3 fold increase), and iNOS (1.6 fold increase) compared to controls (Lu et al, 2013).
- Adult female and male mice have been injected i.p. with 4mg/kg (LD50) of DomA and Real-time PCR has been performed in the brain derived at 30, 60 and 240 min post-injection. The inflammatory response element cyclooxygenase 2 (COX-2) has been found to be 8 fold increased at the 30 and 60 min time points and then showed a descent back toward basal expression levels by 240 min (Ryan et al., 2005).
- Adult male rats treated with 2 mg/kg DomA i.p. have been sacrificed after 3 or 7 d and shown that GFAP and lectin staining could identify regions of reactive gliosis within areas of neurodegeneration however observed at higher magnifications compared to the ones used for neurodegeneration (Appel et al., 1997; Scallet et al., 2005).

- At 5 days and 3 months following DomA administration of male Wistar rats, a large number of OX-42 positive microglial cells exhibiting intense immunoreactivity in CA1 and CA3 regions of the hippocampus have been detected. With an antibody against GFAP, immunoreactive astrocytes have been found to be sparsely distributed in the hippocampus derived from DomA treated rats after 3 months' time interval (Ananth et al., 2003). At 5 days after the administration of DomA, GFAP positive astrocytes have been found increased in the hippocampus (Ananth et al., 2003).

Uncertainties and Inconsistencies

Pb

It is interesting to note that glial cells and in particular astrocytes are able to accumulate lead, suggesting that thes cells may be also a primary target of lead neurotoxic effects (Zurich et al., 1998; Lindhal et al., 1999).

Sobin and coworkers (2013) described a Pb-induced decrease in dentate gyrus volume associated with microglial reactivity at low dose of Pb (30 ppm), but not at high doses (330 ppm), plausibly due to the death of microglial cells at the high dose of Pb.

Pb decreased IL-6 secretion by isolated astrocytes (Qian et al., 2007). Such a decrease was also observed in isolated astrocytes treated with methylmercury, and was reverted in microglia astrocyte co-cultures, suggesting that cell-cell interactions can modify the response to a toxicant and that cultures of a single cell type may not be representative of the organ toxicity (Eskes et al., 2002).

Domoic acid

Adult male and female Sprague Dawley rats have received a single intraperitoneal (i.p.) injection of DomA (0, 1.0, 1.8 mg/kg) and have been sacrificed 3 h after the treatment. Histopathological analysis of these animals has shown no alterations for GFAP immunostaining in the dorsal hippocampus and olfactory bulb, indicating absence of reactive gliosis (Baron et al., 2013).

The exposed zebrafish from the 36-week treatment with DomA showed no neuroinflammation in brain (Hiolski et al., 2014). At the same time, microarray analysis revealed no significant changes in *gfap* gene expression, a marker of neuroinflammation and astrocyte activation (Hiolski et al., 2014).

Domain of Applicability

California sea lions that have been exposed to the marine biotoxin DomA developed an acute or chronic toxicosis marked by seizures, whereas histopathological analysis revealed neuroinflammation characterised by gliosis (Kirkley et al., 2014).

References

Acarin L, González B, Castellano B, Castro AJ. 1997. Quantitative analysis of microglial reaction to a cortical excitotoxic lesion in the early postnatal brain. ExpNeurol 147: 410-417.

Ahmad A, Shah SA, Badshah H, Kim MJ, Ali T, Yoon GH, et al. 2016. Neuroprotection by Vitamin C Against Ethanol-Induced Neuroinflammation Associated Neurodegeneration in the Developing Rat Brain. CNS Neurol Disord Drug Targets 15(3): 360-370.

Ananth C, Thameem DS, Gopalakrishnakone P, Kaur C. Domoic acid-induced neuronal damage in the rat hippocampus: changes in apoptosis related genes (bcl-2, bax, caspase-3) and microglial response. J Neurosci Res., 2001, 66: 177-190.

Ananth C, Gopalakrishnakone P, Kaur C. Induction of inducible nitric oxide synthase expression in activated microglia following domoic acid (DA)-induced neurotoxicity in the rat hippocampus. Neurosci Lett., 2003, 338: 49-52.

Appel NM, Rapoport SI, O'Callaghan JP, Bell JM, Freed LM. Sequelae of parenteral domoic acid administration in rats: comparison of effects on different metabolic markers in brain. Brain Res., 1997, 754: 55-64.

Ashwell K. 1990. Microglia and cell death in the developing mouse cerebellum. DevBrain Res 55: 219-230.

Ashwell K. 1991. The distribution of microglia and cell death in the fetal rat forebrain. DevBrain Res 58: 1-12.

Baratz R, Tweedie D, Wang JY, Rubovitch V, Luo W, Hoffer BJ, et al. 2015. Transiently lowering tumor necrosis factor-alpha synthesis ameliorates neuronal cell loss and cognitive impairments induced by minimal traumatic brain injury in mice. J Neuroinflammation 12: 45.

Baron AW, Rushton SP, Rens N, Morris CM, Blain PG, Judge SJ. Sex differences in effects of low level domoic acid exposure. Neurotoxicology, 2013, 34: 1-8.

Blank T, Prinz M. Microglia as modulators of cognition and neuropsychiatric disorders. Glia, 2013, 61: 62-70.

Cendes F, Andermann F, Carpenter S, Zatorre RJ, Cashman NR. Temporal lobe epilepsy caused by domoic acid intoxication: evidence for glutamate receptor-mediated excitotoxicity in humans. Ann Neurol., 1995, 37: 123-126.

Chandrasekaran A, Ponnambalam G, Kaur C. Domoic acid-induced neurotoxicity in the hippocampus of adult rats. Neurotox Res., 2004, 6:1 05-117.

Chapman GA, Moores K, Harrison D, Campbell CA, Stewart BR, Strijbos PJLM. Fractalkine Cleavage from Neuronal Membrans Represents an Acute Event in Inflammatory Response to Excitotoxic Brain Damage. J Neurosc., 2000, 20 RC87: 1-5.

Dommergues MA, Plaisant F, Verney C, Gressens P. 2003. Early microglial activation following neonatal excitotoxic brain damage in mice: a potential target for neuroprotection. Neuroscience 121(3): 619-628.

Eskes C, Honegger P, Juillerat-Jeanneret L, Monnet-Tschudi F. 2002. Microglial reaction induced by noncytotoxic methylmercury treatment leads to neuroprotection via interactions with astrocytes and IL-6 release. Glia 37(1): 43-52.

Farina C, Aloisi F, Meinl E. Astrocytes are active players in cerebral innate immunity. Trends Immunol, 2007, 28(3): 138-145.

Hayward JH, Lee SJ. A Decade of Research on TLR2 Discovering Its Pivotal Role in Glial Activation and Neuroinflammation in Neurodegenerative Diseases. Experimental Neurobiology, 2014, 23(2): 138-147.

Hiolski EM, Kendrick PS, Frame ER, Myers MS, Bammler TK, Beyer RP, Farin FM, Wilkerson HW, Smith DR, Marcinek DJ, Lefebvre KA., Chronic low-level domoic acid exposure alters gene transcription and impairs mitochondrial function in the CNS. Aquat Toxicol., 2014, 155: 151-159.

Katsumoto A, Lu H, Miranda AS, Ransohoff RM. Ontogeny and functions of central nervous system macrophages. J Immunol., 2014, 193(6): 2615-2621.

Kirkley KS, Madl JE, Duncan C, Gulland FM, Tjalkens RB. Domoic acid-induced seizures in California sea lions (Zalophus californianus) are associated with neuroinflammatory brain injury. Aquat Toxicol., 2014, 156C: 259-268.

Kreutzberg GW. Microglia, the first line of defence in brain pathologies. Arzneimttelforsch, 1995, 45: 357-360.

Kreutzberg GW. Microglia : a sensor for pathological events in the CNS. Trends Neurosci., 1996,19: 312-318.

Lindhal LS, Bird L, Legare ME, Mikeska G, Bratton GR, Tiffany-Castiglioni E. 1999. Differential ability of astroglia and neuronal cells to accumulate lead: Dependence on cell type and on degree of differentiation. ToxSci 50: 236-243.

Liu MC, Liu XQ, Wang W, Shen XF, Che HL, Guo YY, et al., Involvement of microglia activation in the lead induced long-term potentiation impairment. PLoS One, 2012, 7(8): e43924.

Lu J, Wu DM, Zheng YL, Hu B, Cheng W, Zhang ZF, Li MQ. Troxerutin counteracts domoic acid-induced memory deficits in mice by inhibiting CCAAT/enhancer binding protein β-mediated inflammatory response and oxidative stress. J Immunol., 2013, 190: 3466-3479.

Marin-Teva JL, Cuadros MA, Martin-Oliva D, Navascues J., Microglia and neuronal cell death. Neuron glia biology, 2011, 7(1): 25-40.

Mesuret G, Engel T, Hessel EV, Sanz-Rodriguez A, Jimenez-Pacheco A, Miras-Portugal MT, et al. 2014. P2X7 receptor inhibition interrupts the progression of seizures in immature rats and reduces hippocampal damage. CNS neuroscience & therapeutics 20(6): 556-564.

Pulido OM. Domoic acid toxicologic pathology: a review. Mar Drugs, 2008, 6: 180-219.

Qian Y, Zheng Y, Weber D, Tiffany-Castiglioni E. 2007. A 78-kDa glucose-regulated protein is involved in the decrease of interleukin-6 secretion by lead treatment from astrocytes. American journal of physiology Cell physiology 293(3): C897-905.

Ransohoff RM, Brown MA. Innate immunity in the central nervous system. J Clin Invest., 2012, 122(4): 1164-1171.

Rossi D. Astrocyte physiopathology: At the crossroads of intercellular networking, inflammation and cell death. Prog Neurobiol., 2015, 130: 86-120.

Ryan JC, Morey JS, Ramsdell JS, Van Dolah FM. Acute phase gene expression in mice exposed to the marine neurotoxin domoic acid. Neuroscience, 2005, 136: 1121-1132.

Scallet AC, Schmued LC, Johannessen JN. Neurohistochemical biomarkers of the marine neurotoxicant, domoic acid. Neurotoxicol Teratol., 2005, 27: 745-752.

Sobin C, Montoya MG, Parisi N, Schaub T, Cervantes M, Armijos RX. 2013. Microglial disruption in young mice with early chronic lead exposure. Toxicol Lett 220(1): 44-52.

Streit WJ, Conde J, Harrison JK. Chemokines and Alzheimer's disease. Neurobiol Aging., 2001, 22: 909-913.

Struzynska L. 2000. The protective role of astroglia in the early period of experimental lead toxicity in the rat. Acta Neurobiol Exp (Wars) 60(2): 167-173.

Struzynska L, Bubko I, Walski M, Rafalowska U. 2001. Astroglial reaction during the early phase of acute lead toxicity in the adult rat brain. Toxicology 165: 121-131.

Tiwari V, Chopra K. 2012. Attenuation of oxidative stress, neuroinflammation, and apoptosis by curcumin prevents cognitive deficits in rats postnatally exposed to ethanol. Psychopharmacology (Berl) 224(4): 519-535.

Zurich MG, Monnet-Tschudi F, Berode M, Honegger P. 1998. Lead acetate toxicity *in vitro*: Dependence on the cell composition of the cultures. Toxicol *In Vitro* 12(2): 191-196.

Zurich M-G, Eskes C, Honegger P, Bérode M, Monnet-Tschudi F. 2002. Maturation-dependent neurotoxicity of lead aceate *in vitro*: Implication of glial reactions. J Neurosc Res 70: 108-116.

Relationship: 208: N/A, Neuroinflammation leads to N/A, Neurodegeneration

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	adjacent	Moderate	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Moderate	

Key Event Relationship Description

It is well accepted that chronic neuroinflammation is involved in the pathogenesis of neurodegenerative diseases (McNaull et al., 2010; Tansey and Goldberg, 2009; Thundyil and Lim, 2015). Chronic neuroinflammation can cause secondary damage (Kraft and Harry, 2011). The mechanisms by which neuroinflammation (i.e. activated microglia and astrocytes) can kill neurons and induce/exacerbate the neurodegenerative process has been suggested to include the release of nitric oxide that causes inhibition of neuronal respiration, ROS and RNS production, and rapid glutamate release resulting in excitotoxic death of neurons (Brown & Bal-Price, 2003; Kraft & Harry, 2011; Taetzsch & Block, 2013). Glial reactivity is also associated with excessive production and release of pro-inflammatory cytokines that not only affect neurons, but also have detrimental feedback effects on microglia (Heneka et al., 2014). For example, sustained exposure to bacterial lipopolysaccharide (LPS) or to other pro-inflammatory mediators was shown to restrict microglial phagocytosis of misfiled and aggregated proteins (Sheng et al., 2003). Systemic immune challenge during pregnancy leading to microglial activation caused increased deposition of amyloid plaques and tau hyperphosphorylation in aged mice (Krstic et al., 2012, 2013), suggesting that neuroinflammation is involved in the amyloid plaques and neurofibrillary tangles formation. There is further evidence that the formation of neurofibrillary tangles is caused by microglial cell-driven neuroinflammation, since LPS-induced systemic inflammation increased tau pathology (Kitazawa et al., 2005).

Evidence Supporting this KER

Biological Plausibility

Neuroinflammation is a component of neurodegenerative diseases such as Alzheimer's and Parkinson's disease (Neumann, 2001) which may play a secondary or an active primary role in the disease process (Hirsch and Hunot, 2009). McNaull and coworkers (McNaull et al., 2010) suggested that early developmental onset of brain inflammation could be linked with late onset of Alzheimer's disease. A recent paper by Krstic and coworkers (2012) showed that a systemic immune challenge during late gestation predispose mice to develop Alzheimer's like pathology when aging, suggesting a causal link between systemic

inflammation, neuroinflammation, and the onset of Alzheimer's disease. Regarding toxicant-induced neuroinflammation, microglial/astrocyte activation and chronic neuron damage may continue for years after initial exposure (Taetsch and Block, 2013), suggesting that chronic neuroinflammation and neurodegeneration have a slow long-term temporal evolution. Ongoing neuroinflammation can be visualized in patients using the positron emission tomography (PET) ligand [11C] (R)-PK11195 (Cagnin et al., 2001). Recent genome-wide association study (GWAS) analyses of sporadic Alzheimer's disease revealed a set of genes that point to a pathogenic role of neuroinflammation in Alzheimer's disease (for review, see Heneka et al., 2014). High levels of pro-inflammatory cytokines produced by activated microglia and astrocytes are detected in the brain of Alzheimer's subjects and animal models (McGeer and McGeer, 1998; Janelsins et al., 2005).

Empirical Evidence

Pb

Rats treated from gestation day 5 till postnatal day 180 with a mixture of Pb/Cd/As showed in early adulthood increased levels of IL-1b, IL-6 and TNF-a in hippocampus and frontal cortex associated with increased Ab levels, where Pb applied alone triggered maximal Ab induction (Ashok et al., 2015). Similarly, monkeys exposed during infancy to Pb (from birth to 400 days to 1 mg Pb /kg/day) showed in aging (23 y old) an overexpression of APP and Abeta (Bihaqi et al., 2011), and of Tau mRNA and protein (Bihaqi and Zawa, 2013). Similar observations were made in old rats (18-20 months) when exposed to Pb (0.2% in drinking water) from postnatal day 1 to 20 (Basha et al., 2005; Zawia and Basha, 2005; Bihaqi et al., 2014). This was associated with cognitive impairment, observed only if animals were exposed when young (Bihaqi et al., 2014). Perinatal exposure to Pb leading to a blood concentration of 10 mg/dl (a concentration considered as safe for human) promotes Tau phosphorylation in forebrain, cerebellum and hippocampus (Gassowska et al., 2016).

However, adult exposure may also increase the risk of neurodegeneration, as suggested by the two following studies:

- human Tg-SwD1 APP transgenic mice treated with Pb (27 mg/kg/day by gavage) for 6 weeks beginning at 8 weeks of age showed increased accumulation of Abeta and amyloid plaques (Gu et al., 2012).
- former organolead workers had increased tibia Pb level associated with peristent brain damage measured by MRI (Stewart et al., 2006).

Some *in vitro* and *in vivo* experiments show also that neuroinflammation can lead to degeneration:

- the conditioned medium of Pb-treated microglial cells (10 microM for 12h) caused the death of neuroblastoma cells (Kumawak et al., 2014).
- immature 3D cultures treated with Pb for 10 days exhibited neuroinflammation and neuronal death was exacerbated 10 days after the end of treatment, supporting the fact that neuroinflammation leads to neurodegeneration (Zurich et al., 2002).
- *in vivo* and *in vitro* experiments showed that Pb cause microglial activation, which upregulate the levels of pro-inflammatory cytokines (IL-1b, TNF-a) and of iNOS and cause neuronal injury and neuronal death in hippocampus. These effects are significantly reversed by minocycline, an antibiotic blocking microglial reactivity, showing the essential role of neuroinflammation in hippocampal neurodegeneration (Liu et al., 2012)

- gestational exposure of mouse to Pb (0.1 mM in drinking water) led at PND 21 to increased brain mRNA expression of IL-6 and glial finbrillary acidic protein (GFAP) as marker of astrogliosis, as well as of caspase 1 and NOS 2, suggesting a link between Pb-induced neuroinflammation and deletrious effects on neurons (Kasten-Jolly et al., 2011, 2012)

Domoic acid

DomA promotes the expression of inflammatory genes in the brain, such as cyclooxygenase 2 (COX2) and the development of neurodegeneration (Ryan et al., 2005). By using COX2 inhibitors that causes decrease the appearance of DomA-induced neurodegeneration, they have concluded that neuroinflammation contributes towards the development of neurodegeneration (Ryan et al., 2011).

Uncertainties and Inconsistencies

Long-term treatments with NSAIDs (non-steroidal anti-inflammatory drugs) have a preventive effect on Alzheimer's disease development (Piertrzick and Behl, 2005; Wang et al., 2015), but such treatment has no effect or is even detrimental if administered once the disease is at an advanced stage (Lichtenstein et al., 2010), This may be due to the dual protective/destructive effects of neuroinflammation and to its complexity.

Serum Pb level negatively correlates with verbal memory score, but not with abnormal cognition in Alzheimer's disease (Park et al., 2014). Epidemiologic studies are not well-suited to accomodate the long latency period between exposures during early life and late onset of Alzheimer's disease, even if bone Pb content is an accurate measurement of historical Pb exposure in adult (Bakulski et al., 2012).

Besides neuroinflammation or effects associated with neuroinflammation, other mechanisms may be involved in neurodegeneration with Abeta and tau accumulation: Pb-induced epigenetic modifications of genes involved in the amyloid cascade or tau expression may contribute to the accumulation of Abeta and tau accumulation following developmental exposure to Pb (Zawia and Basha, 2005; Basha and Reddy, 2010). Also oxidative damage to DNA was shown to be involved in delayed effects observed in old rats (PD 600), if exposed early postanatally (PD 1 to 20) (Bolin et al., 2006)

Gap of knowledge: there are no studies showing that glufosinate (GLF)-induced neuroinflammation leads to neurodegeneration.

Domain of Applicability

The hypotheisis of developmental origin of Pb-induced neurodegeneration was tested and observed in Zebra fish by Lee and Freeman (2014).

References

Ashok A, Rai NK, Tripathi S, Bandyopadhyay S., Exposure to As-, Cd-, and Pb-mixture induces Abeta, amyloidogenic APP processing and cognitive impairments via oxidative stress-dependent neuroinflammation in young rats. Toxicol Sci., 2015, 143(1): 64-80.

Bakulski KM, Park SK, Weisskopf MG, Tucker KL, Sparrow D, Spiro A, 3rd, et al. 2014. Lead exposure, B vitamins, and plasma homocysteine in men 55 years of age and older: the VA normative aging study. Environ Health Perspect 122(10): 1066-1074.

Basha MR, Murali M, Siddiqi HK, Ghosal K, Siddiqi OK, Lashuel HA, et al. 2005. Lead (Pb) exposure and its effect on APP proteolysis and Abeta aggregation. FASEB J 19(14): 2083-2084.

Basha R, Reddy GR. 2010. Developmental exposure to lead and late life abnormalities of nervous system. Indian journal of experimental biology 48(7): 636-641.

Bihaqi SW, Huang H, Wu J, Zawia NH. 2011. Infant exposure to lead (Pb) and epigenetic modifications in the aging primate brain: implications for Alzheimer's disease. J Alzheimers Dis 27(4): 819-833.

Bihaqi SW, Zawia NH. 2013. Enhanced taupathy and AD-like pathology in aged primate brains decades after infantile exposure to lead (Pb). Neurotoxicology 39: 95-101.

Bihaqi SW, Bahmani A, Subaiea GM, Zawia NH. 2014. Infantile exposure to lead and late-age cognitive decline: relevance to AD. Alzheimer's & dementia : the journal of the Alzheimer's Association 10(2): 187-195.

Bolin CM, Basha R, Cox D, Zawia NH, Maloney B, Lahiri DK, et al. 2006. Exposure to lead and the developmental origin of oxidative DNA damage in the aging brain. Faseb J 20(6): 788-790.

Brown GC, Bal-Price A., Inflammatory neurodegeneration mediated by nitric oxide, glutamate, and mitochondria. Mol Neurobiol., 2003, 27(3): 325-355.

Cagnin A, Brooks DJ, Kennedy AM, Gunn RN, Myers R, Turkheimer FE, et al., In-vivo measurement of activated microglia in dementia. Lancet, 2001, 358(9280): 461-467.

Gassowska M, Baranowska-Bosiacka I, Moczydlowska J, Tarnowski M, Pilutin A, Gutowska I, et al. 2016. Perinatal exposure to lead (Pb) promotes Tau phosphorylation in the rat brain in a GSK-3beta and CDK5 dependent manner: Relevance to neurological disorders. Toxicology 347-349: 17-28.

Gu H, Robison G, Hong L, Barrea R, Wei X, Farlow MR, et al. 2012. Increased beta-amyloid deposition in Tg-SWDI transgenic mouse brain following *in vivo* lead exposure. Toxicol Lett 213(2): 211-219.

Heneka MT, Kummer MP, Latz E., Innate immune activation in neurodegenerative disease. Nat Rev Immunol., 2014, 14(7): 463-477.

Hirsch EC, Hunot S., Neuroinflammation in Parkinson's disease: a target for neuroprotection? Lancet Neurol., 2009, 8: 382-397

Janelsins MC, Mastrangelo MA, Oddo S, LaFerla FM, Federoff HJ, Bowers WJ., Early correlation of microglial activation with enhanced tumor necrosis factor-alpha and monocyte chemoattractant protein-1 expression specifically within the entorhinal cortex of triple transgenic Alzheimer's disease mice. J Neuroinflammation, 2005, 2: 23.

Kasten-Jolly J, Heo Y, Lawrence DA. 2011. Central nervous system cytokine gene expression: modulation by lead. J Biochem Mol Toxicol 25(1): 41-54.

Kasten-Jolly J, Pabello N, Bolivar VJ, Lawrence DA. 2012. Developmental lead effects on behavior and brain gene expression in male and female BALB/cAnNTac mice. Neurotoxicology 33(5): 1005-1020.

Kitazawa M, Oddo S, Yamasaki TR, Green KN, LaFerla FM., Lipopolysaccharide-induced inflammation exacerbates tau pathology by a cyclin-dependent kinase 5-mediated pathway in a transgenic model of Alzheimer's disease. J Neurosci., 2005, 25(39): 8843-8853.

Kraft AD, Harry GJ., Features of microglia and neuroinflammation relevant to environmental exposure and neurotoxicity. International Journal of Environmental research and Public Health., 2011, 8(7): 2980-3018.

Krstic, D., A. Madhusudan, et al., 2012. Systemic immune challenges trigger and drive Alzheimer-like neuropathology in mice. J Neuroinflammation, 2012, 9: 151.

Krstic D, Knuesel I. 2013. Deciphering the mechanism underlying late-onset Alzheimer disease. Nature reviews Neurology 9(1): 25-34.

Kumawat KL, Kaushik DK, Goswami P, Basu A. 2014. Acute exposure to lead acetate activates microglia and induces subsequent bystander neuronal death via caspase-3 activation. Neurotoxicology 41: 143-153.

Lee J, Freeman JL. 2014. Zebrafish as a model for investigating developmental lead (Pb) neurotoxicity as a risk factor in adult neurodegenerative disease: a mini-review. Neurotoxicology 43: 57-64.

Lichtenstein MP, Carriba P, Masgrau R, Pujol A, Galea E., Staging anti-inflammatory therapy in Alzheimer's disease. Frontiers in Aging Neuroscience, 2010, 2: 142.

Liu MC, Liu XQ, Wang W, Shen XF, Che HL, Guo YY, et al. 2012. Involvement of microglia activation in the lead induced long-term potentiation impairment. PLoS One 7(8): e43924.

McGeer PL, McGeer EG., Glial cell reactions in neurodegenerative diseases: Pathophysiology and therapeutic interventions. Alzheimer DisAssocDisord, 1998, 12 Suppl. 2: S1-S6.

McNaull BB, Todd S, McGuinness B, Passmore AP., Inflammation and Anti-Inflammatory Strategies for Alzheimer's Disease - A Mini-Review. Gerontology, 2010, 56: 3-14.

Neumann H., Control of Glial Immune Function by Neurons. Glia, 2001, 36: 191-199

Park JH, Lee DW, Park KS, Joung H. 2014. Serum trace metal levels in Alzheimer's disease and normal control groups. American journal of Alzheimer's disease and other dementias 29(1): 76-83.

Pietrzik, C. and C. Behl., Concepts for the treatment of Alzheimer's disease: molecular mechanisms and clinical application. Int J Exp Pathol., 2005, 86(3): 173-185.

Ryan JC, Morey JS, Ramsdell JS, Van Dolah FM. Acute phase gene expression in mice exposed to the marine neurotoxin domoic acid. Neuroscience 2005. 136: 1121-1132.

Ryan JC, Cross CA, Van Dolah FM. Effects of COX inhibitors on neurodegeneration and survival in mice exposed to the marine neurotoxin domoic acid. Neurosci Lett. 2011. 487: 83-87.

Sheng JG, Bora SH, Xu G, Borchelt DR, Price DL, Koliatsos VE., Lipopolysaccharide-induced-neuroinflammation increases intracellular accumulation of amyloid precursor protein and amyloid beta peptide in APPswe transgenic mice. Neurobiol Dis., 2003, 14(1): 133-145.

Stewart WF, Schwartz BS, Davatzikos C, Shen D, Liu D, Wu X, et al. 2006. Past adult lead exposure is linked to neurodegeneration measured by brain MRI. Neurology 66(10): 1476-1484.

Taetzsch T, Block ML., Pesticides, microglial NOX2, and Parkinson's disease. J Biochem Mol Toxicol., 2013, 27(2): 137-149.

Tansey MG, Goldberg MS., Neuroinflammation in Parkinson's disease: Its role in neuronal death and implications for therapeutic intervention. Neurobiol Dis., 2010, 37(3):510-8.

Thundyil J, Lim KL. 2015. DAMPs and neurodegeneration. Ageing research reviews 24(Pt A): 17-28.

Wang J, Tan L, Wang HF, Tan CC, Meng XF, Wang C, Tang SW, Yu JT (2015) Anti-inflammatory drugs and risk of Alzheimer's disease: an updated systematic review and meta-analysis. J Alzheimers Dis 44: 385-96

Zawia NH, Basha MR. 2005. Environmental risk factors and the developmental basis for Alzheimer's disease. Rev Neurosci 16(4): 325-337.

Zurich M-G, Eskes C, Honegger P, Bérode M, Monnet-Tschudi F. 2002. Maturation-dependent neurotoxicity of lead aceate *in vitro*: Implication of glial reactions. J Neurosc Res 70: 108-116.

Relationship: 207: N/A, Neurodegeneration leads to N/A, Neuroinflammation

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Binding of agonists to ionotropic glutamate receptors in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to learning and memory impairment.	adjacent	Moderate	
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	Moderate	

Key Event Relationship Description

According to its definition, neurodegeneration includes the death of neurons. Therefore, the KER describing the link between cell death and neuroinflammation is also applicable to this KER. However in neurodegenerative diseases and in Alzheimer's disease in particular, neurodegneration is associated with accumulation of modified/aggregated proteins (insoluble amyloid; hyperphosphorylated tau), which are recognised as potential triggers of neuroinflammation:

Proteinopathies associated with neurodegenerative disorders like Alzheimer’s disease (AD) and Parkinson’s disease (PD) may be sensed as damage associated molecular patterns (DAMPs) and thus activate microglia within the CNS. In animal neurodegeneration models and post-mortem brain samples from patients suffering from neurodegenerative disorders often revealed the presence of activated microglia and the accumulation of inflammatory mediators at the lesion sites, which suggests a continuous crosstalk between the brain immune system and the injured neurons during neurodegeneration. Microglial are typically activated acutely in response to an initial triggering insult, but their continued presence in large numbers around the lesion areas may actually promote neuronal death despite the absence of the initial triggering insult. Inflammatory factors being released by dying neurons and/or actively secreted from the activated microglia aid in maintaining the vicious cycle between activated microglia and damaged neurons (Thundyil and Lim 2015).

The fact that neuronal death can trigger neuroinflammation and that neuroinflammation can, in turn, cause neuronal degeneration, is known as a vicious circle, which is involved in the pathogeny of neurodegenerative diseases (Griffin et al., 1998; McGeer and Mc Geer, 1998; Blasko et al., 2004; Cacquevel et al., 2004; Barbeito et al., 2010; Rubio-Perez and Morillas-Ruiz, 2012; Thundyil and Lim, 2015).

Microglial cells are involved in the clearance of amyloid plaques (Querfurth and LaFerla, 2010), but can also be responsible for amyloid plaque formation (Streit and Sparks, 1997). As aging microglia seem to lose their ability to phagocytose (Floden and Combs, 2011), impaired clearance, as well as active deposition, can both contribute to amyloid plaque accumulation.

Evidence Supporting this KER

Biological Plausibility

In Alzheimer's disease, Griffin and coworkers (1997) described the presence of reactive microglial cells inside the amyloid plaques and of reactive astrocytes around the plaques. Intra-cerebroventricular injections of beta-amyloid resulted in age-related increase in cholinergic loss and microglial activation (Nell et al., 2014). Increased neuronal expression of presequence protease (PreP) decreased the accumulation of beta-amyloid in synaptic mitochondria and decreases the neuroinflammatory response (Du Fang et al., 2015), showing a link between the accumulation of insoluble proteins and neuroinflammation. In addition, presence of the apolipoprotein E4 (APOE) allele, which is the strongest genetic risk factor for the development of Alzheimer's disease, increases microglial reactivity in the amyloid plaques of a mouse model of beta-amyloid deposition, suggesting a role for APOE in modulation beta-amyloid-induced neuroinflammation in Alzheimer's disease progression (Rodriguez et al., 2014).

Empirical Evidence

Binding of agonists to N-methyl-D-aspartate receptor (NMDAR) in adult brain causes excitotoxicity that mediates neuronal cell death, contributing to reduction (or loss) of cognitive function

DomA (0.75 mg/kg body weight) when administered intravenously in adult rats reveals neuronal degeneration followed by glial activation (Ananth et al., 2001; 2003). More specifically, 5 days after DomA administration, Nissl staining of brain sections derived from DomA-treated animals have shown extensive neuronal damage in the pyramidal neurons of CA1, CA3 subfields and hilus of the dentate gyrus in the hippocampus. In the same brain areas, neuroinflammation has also been evident characterised by increased GFAP and OX-42 immunoreactivity at 5 days after DomA administration but not earlier (24 h) (Ananth et al., 2003). Previously, the same research team has shown increased number of stained degenerated neurons in the hippocampus by Nissl staining as early as 24 h following the administration of DomA, however, the degeneration has been found to be more severe after 5 days (Ananth et al., 2001).

Uncertainties and Inconsistencies

Gap of knowledge: there are no studies showing that glufosinate-induced neurodegeneration leads to neuroinflammation.

References

Ananth C, Thameem Dheen S, Gopalakrishnakone P, Kaur C. Domoic acid-induced neuronal damage in the rat hippocampus: changes in apoptosis related genes (bcl-2, bax, caspase-3) and microglial response. J Neurosci Res., 2001. 66: 177-190.

Ananth C, Gopalakrishnakone P, Kaur C. Protective role of melatonin in domoic acid-induced neuronal damage in the hippocampus of adult rats. Hippocampus, 2003. 13:375-87.

Barbeito AG, Mesci P, Boillee S., Motor neuron-immune interactions: the vicious circle of ALS. J Neural Transm., 2010, 117(8): 981-1000.

Blasko I, Stampfer-Kountchev M, Robatscher P, Veerhuis R, Eikelenboom P, Grubeck-Loebenstein B. 2004. How chronic inflammation can affect the brain and support the

development of Alzheimer's disease in old age: the role of microglia and astrocytes. Aging cell 3(4): 169-176.

Cacquevel M, Lebeurrier N, Cheenne S, Vivien D. Cytokines in neuroinflammation and Alzheimer's disease. Curr Drug Targets., 2004, 5(6): 529-534.

Fang D, Wang Y, Zhang Z, Du H, Yan S, Sun Q, et al., Increased neuronal PreP activity reduces Abeta accumulation, attenuates neuroinflammation and improves mitochondrial and synaptic function in Alzheimer disease's mouse model. Human molecular genetics, 2015, 24(18): 5198-5210.

Griffin.W.S.T., Sheng J, Mrak R., Inflammatory Pathways. Implications in Alzheimer's disease. Humana Press Inc., 1997, 0: 169-176.

Floden AM, Combs CK. 2011. Microglia demonstrate age-dependent interaction with amyloid-beta fibrils. J Alzheimers Dis 25(2): 279-293.

Griffin, W. S., J. G. Sheng, et al., Glial-neuronal interactions in Alzheimer's disease: the potential role of a 'cytokine cycle' in disease progression. Brain Pathol., 1998, 8(1): 65-72.

Hayward JH, Lee SJ. A Decade of Research on TLR2 Discovering Its Pivotal Role in Glial Activation and Neuroinflammation in Neurodegenerative Diseases. 2014, Experimental neurobiology, 23(2): 138-147.

McGeer PL, McGeer EG., Glial cell reactions in neurodegenerative diseases: Pathophysiology and Therapeutic Interventions. Alzheimer DisAssocDisord 12 Suppl. 1998, 2: S1-S6.

Nell HJ, Whitehead SN, Cechetto DF., Age-Dependent Effect of beta-Amyloid Toxicity on Basal Forebrain Cholinergic Neurons and Inflammation in the Rat Brain. Brain Pathol., 2015, 25(5): 531-542.

Querfurth HW, LaFerla FM. 2010. Alzheimer's disease. The New England journal of medicine 362(4): 329-344.

Rodriguez GA, Tai LM, LaDu MJ, Rebeck GW., Human APOE4 increases microglia reactivity at Abeta plaques in a mouse model of Abeta deposition. J Neuroinflammation, 2014, 11: 111.

Rubio-Perez JM, Morillas-Ruiz JM.,A review: inflammatory process in Alzheimer's disease, role of cytokines. Scientific World Journal, 2012: 756357.

Streit WJ, Sparks DL. 1997. Activation of microglia in the brains of humans with heart disease and hypercholesterolemic rabbits. JMolMed 75: 130-138.

Thundyil J, Lim KL., DAMPs and Neurodegeneration. Ageing research reviews. 2015, 24(Pt A):17-28

Relationship: 1069: N/A, Neurodegeneration leads to Impairment, Learning and memory

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Chronic binding of antagonist to N-methyl-D-aspartate receptors (NMDARs) during brain development leads to neurodegeneration with impairment in learning and memory in aging	adjacent	High	

Key Event Relationship Description

Animal models of neurodegenerative diseases, in particular Alzheimer's disease, contributed to the elucidation of the link between amyloid protein and tau hyperphosphorylation and cognitive deficits. Bilateral injections of amyloid-b peptide in the frontal cortex of rats lead to progressive decline in memory and neurodegeneration in hippocampus (for review see Eslamizade et al., 2016). Recent findings have shown that soluble forms of Ab rather than insoluble forms (fibrils and plaques) are associated with memory impairment in early stages of Alzheimer's disease (for review see Salgado-Puga and Pena-Ortega, 2015). Several lines of evidence suggest that the small oligomeric forms of Ab and tau may act synergistically to promote synaptic dysfunction in Alzheimer's disease (for review see Guerrerro-Minoz et al., 2015). Some reports proposed the concept of imbalance between production and clearance of Ab42 and related Ab peptides, as an initiating factor inducing hyperphosphorylation of tau and leading to neuritic dystrophy and synaptic dysfunction (for review see Selkoe and Hardy, 2016). Recent trials of three different antibodies against amyloid peptides have suggested a slowing of cognitive decline in post hoc analyses of mild Alzheimer subjects (for review see Selkoe and Hardy, 2016). Therefore cognitive deficits may be related to the level and extent of classical Alzheimer pathology landmarks, but it is also influenced by neurodegeneration (for review see Braskie and Thompson, 2013). Indeed decreased hippocampal volume due to widespread neurodegeneration and visualized by neuroimaging appears to be a significant predictor of memory decline (for review see Braskie and Thompson, 2016).

Evidence Supporting this KER

Biological Plausibility

It is well accepted that impairment of cell function or cell loss in hippocampus will interfere with memory processes, since the hippocampus plays a key role in memory (Barker and Warburton, 2011). In Alzheimer's disease, hippocampus and entorhinal cortex are affected early in the disease process and cognitive deficit is correlated with brain atrophy (for review Braskie and Thompson, 2013).

Empirical Evidence

Pre-natal and post-natal Pb exposure affects the hippocampus and the frontal cortex (Schneider et al., 2012). Rats exposed to Pb exhibit microglial activation, and upregulation of the level of IL-1b, TNF-a and iNOS, and these pro-inflammatory factors may cause

hippocampal neuronal injury as well as Long Term Potentiation (LTP) deficits, These results suggest a direct link between Pb-induced neuroinflammation, neurodegeneration in hippocampus, and memory deficit (Liu et al., 2012). These effects are reversed by minocycline, an antibiotic which decreases microglial activation, strengthening the link between neuroinflammation, neurodegeneration and memory impairment. In epidemiological studies of adults, cumulative lifetime exposure to Pb has been associated with accelerated declines in cognition (Bakulski et al., 2012). In a study aiming at determining whether serum trace metals are related to abnormal cognition in Alzheimer's disease, it was found that serum Pb levels were significantly negatively correlated with verbal memory scores (Park et al., 2014). Cognitive impaiment was observed in mice exposed to Pb as infants but not as adults, suggesting that a window of vulnerability to Pb neurotoxicity can influence Alzheimer pathogenesis and cognitive decline in old age (Bihaqui et al., 2014). Human Tg-SWDI APP transgenic mice, which over-express amyloid plaques at age of 2-3 months, received oral gavage of 50 mg/kg of Pb once daily for 6 weeks. They showed a significant increase of Abeta in the CSF, brain cortex and hippocampus associated to impaired spatial learning ability, suggesting that Pb facilitates Abeta fibril formation and participate in deposition of amyloid plaques (Gu et al.,2011, 2012),

Uncertainties and Inconsistencies

There are some inconsistencies regarding the time of exposure. Some papers clearly show that early Pb exposure increases amyloid and tau pathology and cognitive decline in aging. But few studies have addressed this complex question by using an ad hoc experimental design. Other studies have descibed the effects of lifetime or long-term exposure on cognitive functions but without a precise desciption of exposure onset and duration.

References

Bakulski KM, Park SK, Weisskopf MG, Tucker KL, Sparrow D, Spiro A, 3rd, et al. 2014. Lead exposure, B vitamins, and plasma homocysteine in men 55 years of age and older: the VA normative aging study. Environ Health Perspect 122(10): 1066-1074.

Barker GR, Warburton EC. 2011. When is the hippocampus involved in recognition memory? J Neurosci 31(29): 10721-10731.

Bihaqi SW, Bahmani A, Subaiea GM, Zawia NH. 2014. Infantile exposure to lead and late-age cognitive decline: relevance to AD. Alzheimer's & dementia : the journal of the Alzheimer's Association 10(2): 187-195.

Braskie MN, Thompson PM. 2013. Understanding cognitive deficits in Alzheimer's disease based on neuroimaging findings. Trends in cognitive sciences 17(10): 510-516.

Eslamizade MJ, Madjd Z, Rasoolijazi H, Saffarzadeh F, Pirhajati V, Aligholi H, et al. 2016. Impaired Memory and Evidence of Histopathology in CA1 Pyramidal Neurons through Injection of Abeta1-42 Peptides into the Frontal Cortices of Rat. Basic and clinical neuroscience 7(1): 31-41.

Gu H, Wei X, Monnot AD, Fontanilla CV, Behl M, Farlow MR, et al. 2011. Lead exposure increases levels of beta-amyloid in the brain and CSF and inhibits LRP1 expression in APP transgenic mice. Neurosci Lett 490(1): 16-20.

Gu H, Robison G, Hong L, Barrea R, Wei X, Farlow MR, et al. 2012. Increased beta-amyloid deposition in Tg-SWDI transgenic mouse brain following *in vivo* lead exposure. Toxicol Lett 213(2): 211-219.

Guerrero-Munoz MJ, Gerson J, Castillo-Carranza DL. 2015. Tau Oligomers: The Toxic Player at Synapses in Alzheimer's Disease. Frontiers in cellular neuroscience 9: 464.

Liu MC, Liu XQ, Wang W, Shen XF, Che HL, Guo YY, et al. 2012. Involvement of microglia activation in the lead induced long-term potentiation impairment. PLoS One 7(8): e43924.

Park JH, Lee DW, Park KS, Joung H. 2014. Serum trace metal levels in Alzheimer's disease and normal control groups. American journal of Alzheimer's disease and other dementias 29(1): 76-83.

Salgado-Puga K, Pena-Ortega F. 2015. Cellular and network mechanisms underlying memory impairment induced by amyloid beta protein. Protein and peptide letters 22(4): 303-321.

Schneider JS, Anderson DW, Talsania K, Mettil W, Vadigepalli R. 2012. Effects of developmental lead exposure on the hippocampal transcriptome: influences of sex, developmental period, and lead exposure level. Toxicol Sci 129(1): 108-125.

Selkoe DJ, Hardy J. 2016. The amyloid hypothesis of Alzheimer's disease at 25 years. EMBO molecular medicine 8(6): 595-608.