What is the tryptophan kynurenine pathway and why is it important to neurotherapeutics?

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The kynurenine pathway has received increasing attention as its connection to inflammation, the immune system and neurological conditions has become more apparent. It is the primary route for tryptophan catabolism in the liver and the starting point for the synthesis of nicotinamide adenine dinucleotide in mammals. Dysregulation or overactivation of this pathway can lead to immune system activation and accumulation of potentially neurotoxic compounds. These aspects make the kynurenine pathway a promising target for therapeutic development to treat inflammation and disease with neurological aspects, especially in cancer patients undergoing chemotherapy.

Tryptophan is an essential amino acid that is used to build protein and is a biosynthetic precursor to numerous neurologically active compounds. It is probably most well known as the starting point for the biosynthesis of serotonin and melatonin. While the generation of these two compounds may have garnered the most attention in the past, a less well-known pathway for tryptophan metabolism, the kynurenine pathway, has recently seen steadily increasing research activity. The importance of the kynurenine pathway, which accounts for the catabolism of approximately 99% of ingested tryptophan not used for protein synthesis [1], was originally ascribed to its role in the biogenesis of nicotinamide adenine dinucleotide (NAD); however, apparent links with neurodegenerative diseases, tumor proliferation, inflammation and depression are currently driving the study of the kynurenine pathway.

The kynurenine pathway was first discovered in 1853 through the detection of excreted products from animals fed tryptophan. In the ensuing century, much work was performed to establish the chemical transformations, enzymes involved, and possible disease relations of the kynurenine pathway. In the 1960s, the component enzymes of the kynurenine pathway were fully elucidated through the laborious work of extracting each component enzyme from mammalian tissue and determining their corresponding activities [2].

As the link between the kynurenine pathway and major depressive disorder became more apparent, the serotonin hypothesis was proposed, stating that upon activation, the kynurenine pathway would divert available tryptophan away from serotonin production towards further catabolism [3]. Although the correlation between kynurenine pathway activity and inflammation has been confirmed in many instances, the serotonin hypothesis has not survived in its original form. It was shown that kynurenine pathway activation by IFN-α did not significantly lower the tryptophan concentration in cerebrospinal fluid, although it did lead to inflammation by increasing the amounts of kynurenine pathway metabolites, namely kynurenine, kynurenic acid and quinolinic acid (QUIN), concentrations in cerebrospinal fluid [4]. Inflammation caused by kynurenine pathway activation has also been implicated in the treatment resistance of

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some patients suffering from depression as well as with patients undergoing chemotherapy [5].

Thanks to modern molecular biological methods, as well as the discovery of analogous kynurenine pathways in bacterial species [6], it recently became possible to study the individual enzymes of the kynurenine pathway at the molecular level. The first and rate-limiting step of the kynurenine pathway is catalyzed by tryptophan 2,3-dioxygenase (TDO) or indoleamine 2,3-dioxygenase (IDO). These heme-dependent enzymes insert molecular oxygen across the 2–3 bond of the indole moiety of tryptophan [7] and were formerly known as tryptophan pyrrolase. TDO is a homotetramer with rigid substrate selectivity which is found mostly in hepatic tissue, whereas IDO is a monomer with much more relaxed specificity that is found in most tissues. Notably, IDO is increasingly recognized as a link between the immune system and the kynurenine pathway, as it is activated by cytokines and appears to have some anti-inflammatory effects. It is also implicated in the tumor-suppressive abilities of IFN-γ [8]. From a mechanistic enzymology viewpoint, these enzymes are unique, as they are the only known dioxygenases that employ a heme prosthetic group as a cofactor. Furthermore, IDO is the only enzyme, other than superoxide dismutase that can utilize superoxide as a substrate, implicating it in oxidative stress response.

The product of the TDO/IDO-catalyzed reaction, *N*-formylkynurenine, is then hydrolyzed to kynurenine. Depending on the tissue type, kynurenine either continues down its pathway toward the tricarboxylic acid cycle or is transformed to kynurenic acid in microglial cells or astrocytes, respectively [9]. Kynurenine and its immediate metabolites do not appear to have any direct effects on neurons; however, they do possess various pro- and antioxidant activities. Alternatively, kynurenic acid competitively antagonizes glutamate receptors and non-competitively inhibits the α7 nicotinic acetylcholine receptor [9].

Further down the kynurenine pathway, a second dioxygenase, 3-hydroxyanthranilic acid dioxygenase (HAO), is utilized to open the remaining aromatic ring that once belonged to tryptophan. HAO is a type III, non-heme, iron-dependent extradiol dioxygenase [10]. Although not as unique as TDO/IDO, HAO still has interesting features. Notably, HAOs from bacterial sources often contain an extra, rubredoxin-like metal binding domain that is not necessary for catalysis. This domain is not found in HAOs from animal sources, raising the question as to the function and significance of such an extra metal binding domain. HAO cleaves the ring of 3-hydroxyanthranilic acid, a known free radical generator, to create α-amino-β-carboxymuconate-ε-semialdehyde, a compound that decays non-enzymatically to the NAD precursor, QUIN. The renewed interest in the kynurenine pathway is due in large part to the discovery that QUIN can selectively activate NMDA receptors [11,12]. Although the basal levels of QUIN are not such that they can significantly excite NMDA receptors, activation of the kynurenine pathway can lead to dangerous QUIN levels, which are associated with numerous neurological diseases: Alzheimer's disease, anxiety, depression, epilepsy, human immunodeficiency virus-associated neurocognitive disorders and Huntington's disease [11,13–17]. The generation of QUIN is thought to be the major link between the kynurenine pathway and inflammatory response [18].

The next enzyme in the kynurenine pathway not only exhibits unique chemistry but is also the major branching point between a non-enzymatic formation of the excitotoxic NAD precursor, QUIN and further metabolism. This enzyme is α-amino-β-carboxymuconate-ε-semialdehyde decarboxylase (ACMSD), the only known metal-dependent, oxygen-independent decarboxylase. The x-ray crystal structure of this enzyme was recently solved, and biochemical work has shown a potential mechanism for regulating the activity of this enzyme. It was shown that only the homo-dimer form of ACMSD is able to catalyze the decarboxylation of the substrate, opening the door to the possibility that modulation of the quaternary structure of ACMSD may be the dominant regulatory mechanism for this enzyme [19,20]. Another interesting feature of ACMSD is that both its substrate and product are unstable and will undergo electrocyclizations to QUIN and picolinic acid, respectively. Although there is a wealth of studies showing the deleterious effects of QUIN, the literature on picolinic acid is sparse, and no consensus has yet been reached as to its physiological roles and effects [21]. It seems to represent a metabolic dead-end for the kynurenine pathway, as it is excreted.

At least in the *in vitro* studies, the substrate of ACMSD is an order of magnitude more stable than its product [22], which brings up the natural question of how the rates of these two non-enzymatic decay reactions are controlled in the cell. Answering this question will require detailed knowledge of the enzymatic mechanism of HAO, ACMSD, and the next enzyme in the pathway, α-aminomuconate-ε-semialdehyde dehydrogenase (AMSDH). The structure and mechanism of ACMSD are relatively well studied [19,20], and the structure of HAO is defined [23]. However, little was known about this third enzyme, which presumably controls the partitioning between further metabolism and picolinic acid formation, until very recently, when the crystal structure was solved, and catalytic mechanism proposed [22]. α-Aminomuconate-ε-semialdehyde dehydrogenase (AMSDH) is a member of the aldehyde dehydrogenase superfamily and the first energy harvesting step of the kynurenine pathway, oxidizing its semialdehyde substrate while reducing NAD.

To summarize, the primary metabolic route for tryptophan catabolism in mammals produces neuroactive compounds, one of which, QUIN, is both the biosynthetic precursor to NAD production and an agonist of NMDA receptors. Elevation of QUIN concentrations in cerebrospinal fluids has been seen in several neurodegenerative diseases, and injection of exogenous QUIN can cause neurodegeneration in mice. The kynurenine pathway can be stimulated in the brain by treatment with IFN-α. These findings point to the production of QUIN by the kynurenine pathway as a contributing factor to neurodegenerative diseases that are associated with inflammation.

In conclusion, the kynurenine pathway is the major route for tryptophan catabolism in mammalian cells, and many of the

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intermediates and products of this pathway are implicated in numerous neurological diseases. As such, the kynurenine pathway is a ripe target for drug discovery, especially because so little is known regarding its regulation. The kynurenine pathway also has some connection to tumor growth and proliferation through one of its initiating enzymes, IDO, and there are IDO inhibitors currently in Phase II clinical trials [24]. In recent years, the kynurenine pathway has received increased attention from clinicians, biologists, and biochemists as its medical relevance became more apparent. Even with the renewed effort, there is still a lack of understanding of how the production of arguably the most detrimental metabolite, QUIN, is controlled and work must be done to target its production therapeutically. There is a current need for investigations into the mechanisms by which the kynurenine pathway is regulated, especially the enzymes involved in QUIN formation.

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