The role of impaired de novo Coenzyme A biosynthesis in pantothenate kinase-associated neurodegeneration
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2010

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Download date: 12-12-2019
Summarizing discussion

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Manuscript in preparation for review
**SUMMARIZING DISCUSSION**

Pantothenate kinase-associated neurodegeneration (PKAN, OMIM 234200) is an autosomal recessive, progressive neurodegenerative disorder. PKAN is caused by mutations in pantothenate kinase 2 (PANK2), the gene that encodes an enzyme (PANK2) which is a rate limiting enzyme in de novo Coenzyme A (CoA) biosynthesis. Interestingly, in humans there are four highly homologous PANK genes (PANK1-4) however; only mutations in PANK2 but not in the other PANK genes, are associated with PKAN. Mutations in PANK1, 3, 4 have also never been reported to be associated with any other diseases or pathologies, suggesting that, these genes are essential for life, or their functions may be redundant. Since PANK is the first and the rate limiting enzyme in de novo CoA biosynthesis, the suggestion was postulated that impairment of de novo CoA biosynthesis might underlie the pathogenesis of PKAN [1]. Interestingly, among the four PANKs, only PANK2 is targeted to the mitochondria and these organelles have the highest concentration of total cellular pool of CoA. Therefore, it was also proposed that a mitochondrial deficiency of CoA biosynthesis results in the PKAN disorder. In order to investigate these hypotheses and to understand how a deficiency in PANK2 might give rise to the neuropathology of PKAN, a mouse PANK2 knock-out model was generated [2]. Unfortunately, the mouse model was unable to recapitulate the neurodegenerative symptoms of PKAN. Therefore, currently, the PKAN pathology remains complex and far from understood and due to the lack of a proper PKAN model, the speculated role of impaired de novo CoA remained uninvestigated. In addition, the rarity of PKAN patients (1:3,000,000) complicates investigating PKAN pathology, because patient material is extremely sparse. *Drosophila* is a well established model organism to understand mechanisms in health and disease and also based on the above, it would be helpful for PKAN-related research to have a *Drosophila* PKAN model. Here, we explored the possibilities of *Drosophila* as a model for PKAN and we investigated the implicated role of impaired de novo CoA biosynthesis in the pathogenesis of this devastating disease. Specifically we were interested in determining; 1) whether the PANK deficiency in *Drosophila* indeed leads to a CoA deficiency. 2) Whether CoA deficiency in an organism (*Drosophila*) can lead to a neurodegenerative disorder. If successful, our aim was to use the power of the *Drosophila* model to screen various compounds, which can ameliorate the PKAN disease characteristics.

**Impaired de novo CoA biosynthesis in Drosophila results in PKAN like disorder**

*De novo* CoA biosynthesis occurs in a conserved metabolic route where VitB5 is converted into CoA by the action of five enzymes: PANK, PPCS, PPCDC, PPAT and DPCK. We demonstrated that *Drosophila* mutants for *dPANK/fbl, dPPCS, dPPAT-DPCK* (referred to as CoA mutants) can be used to study the consequences of impaired de novo CoA biosynthesis in higher eukaryotes (Chapter 2). The *Drosophila* CoA mutants are neurologically impaired, are highly sensitive to ROS or irradiation and have a reduced life span (Chapter 2). These findings strengthened the hypothesis that defective CoA biosynthesis induces a
neurodegenerative phenotype and might be one of the underlying causes of PKAN pathogenesis. We also showed that dPANK/fbl mutants have severe deficits in the total cellular pool of CoA (Chapter 3). Clearly, impaired function of dPANK results in a decreased CoA pool and thereby, possibly inducing a neurodegenerative phenotype and a reduced lifespan in dPANK mutants. In support of this, recently a mice study demonstrated that deprivation of Vit B5 (substrate of PANK and precursor for CoA biosynthesis) results in movement disorders possibly due to impairment of CoA biosynthesis [3]. Similarly, chemically blocking the PANK enzyme function by a competitive inhibitor of Vit B5 (HoPan) also results in decreased levels of CoA and a reduced life span of the treated mice, although neurodegeneration was not reported [4]. These combined findings clearly implicate the role of impaired de novo CoA biosynthesis in life span determination and neurodegeneration.

Our study also demonstrated that dPANK mutants have severe mitochondrial defects (Chapter 3). Contrary to human and mice, Drosophila has only one PANK gene (dPANK). However, this dPANK/fbl gene has five splice isoforms and interestingly one of them (dPANK-E) is predicted to be targeted to mitochondria [5]. Remarkably, only mitochondrial targeted dPANK-E is the most potent isoform in rescuing the phenotype of dPANK/fbl mutants [5]. This finding indirectly indicates that mitochondrial defects might be the major contributors to the PKAN-like characteristics in Drosophila. hPANK2 and hPPAT-DPCK are the enzymes that catalyze the first and last step of CoA biosynthesis respectively and both of these enzymes are mitochondrial localized [1, 6, 7]. Recently, hPANK2 is shown to be a sensor of palmitoylcarnitine and thereby proposed to regulate the mitochondrial de novo CoA biosynthesis. Similar to mutations in dPANK/fbl, it is possible that defects in hPANK2 also lead to severe mitochondrial perturbations. This is consistent with the observation in mice that chemical inhibition of PANK by HoPan lead to a decrease in the hepatic CoA pool and severe mitochondrial pathology (swollen mitochondria [4]. Mitochondrial defects are shown to affect tissues with a high energy demand like the brain [8-10] and this might explain why a defect in PANK2 results in a neurodegeneration of specific areas of the brain. There are several patients with clinical symptoms of PKAN (idiopathic PKAN) that do not carry mutations in PANK2 gene. This implies that there are more causative genes (yet to be investigated) and hPPAT-DPCK might be one of them. Although, a group of 72 NBIA patients was screened for gene mutations in other enzymes of CoA biosynthesis however, none of the genes coding for the other CoA enzymes were affected [11]. This finding however, does not exclude the possibility that in the future hPPAT-DPCK mutations might be identified in these idiopathic NBIA patients. It is also possible that mutations in hPPAT-DPCK are embryonic lethal and thus can never be identified.

In summary, impaired function of the PANK enzyme either due to mutations in the PANK gene (Chapter 2 and 3.) or due to chemical inhibition of PANK [4] lead to a decrease in de novo CoA biosynthesis. Furthermore, impairment of de novo CoA biosynthesis results in PKAN like characteristics in Drosophila (this thesis).
Pantethine restores CoA levels and rescues *Drosophila dPANK/fbl* mutants

Pantethine can rescue CoA deficiency and thereby rescues the PKAN-like characteristics in *Drosophila* (Chapter 3). Although the finding that pantethine can be converted into CoA is not novel [12-14], our finding that pantethine can be physiologically converted into CoA in the absence of PANK is quite remarkable (Chapter 3). This finding elucidates a novel pathway of pantetheine conversion from pantethine to CoA independent from pantothenate kinase. This is very relevant for PKAN patients, who suffer from impaired function of PANK2.

Pantethine is known since 1950s as a naturally occurring compound that constitutes part of the CoA molecule [13]. It was initially identified as L. bulgaricus growth factor (LBF) [15, 16] and later biochemically shown to be a substrate for *de novo* CoA biosynthesis ([13] and figure 1).

![Figure 1: Figure adapted from J Bacteriology 1951 March; 61(3): 283–291.](image)

*One of the first few reports in which Pantethine was shown to be converted into pantetheine (monomeric form of pantethine). Later, Pantetheine was suggested to be converted into either CoA by the intestinal enzymes or Pantothenic acid by the liver enzymes.*

In a biochemical conversion of pantethine into CoA, pantetheine must be phosphorylated into 4’-phosphopantetheine that is then suggested to be converted into CoA by the action of PPAT-DPCK [17, 18]. Using a crude cellular extract for an enzyme study, it was shown that a fraction from this crude mix has a potency to phosphorylate pantothenic acid and pantethine [19-21]. This enzyme fraction was termed as pantothenate kinase and since then it was assumed that pantothenate kinase is also the kinase, which phosphorylate pantetheine. Recently in a biochemical assay, pantetheine was shown to be readily phosphorylated by PANK3 [22]. Therefore, it might be possible that the earlier suggestions of
conversion of pantethine to 4’-phosphopantetheine by PANK is physiologically feasible. Although, presence of another kinase was never excluded that has a potency to phosphorylate pantetheine (a so called potential pantetheine kinase). In our experiments, pantethine can also be converted into CoA however in absence, or at least in the presence of severely reduced levels of PANK. Our findings are in contrast to the earlier assumption that PANK is the only kinase capable of phosphorylating pantetheine and hints towards the presence of another potential, yet unidentified, pantetheine kinase.

Figure 2: Possible pathways for de novo CoenzymeA biosynthesis.

In canonical de novo CoA biosynthesis pathway, vitamin B5 (pantothenic acid) is converted into CoA by the consecutive action of five enzymes: PANK, PPCS, PPCDC, PPAT and DPCK. Pantethine may be converted to pantetheine; pantetheine may be phosphorylated by a yet-unknown pantetheine kinase, other than pantothenate kinase (indicated by kinase X). Phosphorylated pantetheine (4’-phosphopantetheine) may enter the canonical de novo CoA biosynthesis pathway downstream of PPCDC and upstream of PPAT.

Based on the results of Chapter 3 and the above we hypothesize that at least in Drosophila there might be a so far unknown kinase which can catalyze the conversion of pantetheine into 4’-phosphopantetheine (Figure 2, kinase X). Identification of such a kinase is of prime importance because it strengthens the presence of a novel pathway of pantetheine conversion into CoA and it is of direct relevance to design strategies to treat PKAN.

We show that pantethine is a promising compound and can ameliorate the PKAN-like-characteristics in Drosophila. As a step further, studies must be undertaken to test its efficacy in mammalian models and then finally in PKAN patients. Pantethine is not a FDA approved drug and therefore it needs extensive further pharmacological tests. In our experiments, we have shown that pantethine at a high dose can be toxic (Chapter 3) and thus, toxicological studies for pantethine must be performed. We tested various doses in mice (Chapter 4) and demonstrated that around 4000 mg/body wt/day is well tolerated by mice and this study may serve as a base for future testing the potential of pantethine in mice. Pantethine has already been used in several human clinical trials as a drug for dyslipidaemia and patients can tolerate a dose of pantethine up to 15 mg/body wt/day. These observations surely suggest that testing pantethine in PKAN patients is possible within the near future. Because PKAN is a brain disease, it is highly relevant to investigate whether pantethine is able to cross the blood brain barrier (BBB). In a study aiming at treating cerebral malaria, thiol-pantethine appeared to be effective, suggesting that pantethine might cross the blood brain barrier (BBB) [23]. However, thorough investigations regarding pantethine’s potency
to cross the BBB must be performed. In summary, pantethine may serve as a starting point to develop a possible treatment for PKAN however, there are still several key issues to be resolved.

Moonlighting role of PANK

Pantethine rescues CoA levels in the Drosophila model for PKAN (Chapter 3). Interestingly, restoration of CoA rescues all the neurodegeneration-associated phenotypes however, the male and female fertility (Chapter 5) were not rescued (unpublished observations). There can be several explanations for these observations. It is likely that pantethine, when supplemented through the food, is unable to reach the reproductive organs. Therefore, pantethine is unable to restore the local CoA deficits in the reproductive organs and fertility defects in male and females cannot be rescued. It is also possible that CoA levels needs to be tightly regulated in the reproductive organs and rescue by pantethine does not result in exact restoration of the endogenous intracellular levels of CoA. Intriguingly, another reason could be that dPANK/fbl might have an additional function apart from being a CoA biosynthesis enzyme. Recently, several proteins, including some metabolic enzymes, were reported to have more than one function in various cellular processes [24]. Such proteins are referred to as moonlight proteins and comprise an interesting subset of multifunctional proteins, in which two unrelated functions (moonlighting functions) are found in a single polypeptide chain [25]. It is an intriguing hypothesis that dPANK/fbl may be a moonlight protein that possesses an additional novel function apart from being a metabolic enzyme. In support of this hypothesis, in a yeast-two-hybrid experimental setup, dPANK/fbl was shown to physically interact with Twinstar (Tsr) [26]. Tsr is a human cofilin-like actin depolymerizing factor involved in the physiological turnover of actin and thereby influencing actin dynamics [27]. The physiological protein-protein interaction between dPANK/fbl and Tsr needs to be confirmed with additional essays and its biological relevance needs to be investigated as well. However, in case an interaction between dPANK/fbl and Tsr does exist, this points further to dPANK/fbl as a moonlighting protein. It is possible that in dPANK/fbl mutants, the interaction between dPANK/fbl and Tsr is disturbed and this explains the actin polymerization defects that we have reported in the dPANK/fbl mutants (Chapter 5). This is further supported by the fact that the actin defects in dPANK/fbl are not quite similar as the actin defects observed in the other CoA mutants and by the observation that pantethine treatment does not rescue the male and female fertility. Although, it will be a key experiment to measure CoA levels in the mutant testis and oocytes of the pantethine-treated mutants. This interesting hypothesis can be further investigated by determining the tsr-dPANK/fbl interaction sites, mutating these sites and thereby block their interaction and studying the induced phenotype. Further insight regarding possible moonlighting functions of dPANK might be obtained from a micro array study in which the transcriptome was compared between the following conditions. 1) Control Schneider S2 cells; 2) Control Schneider S2 cells treated with pantethine; 3) dPANK/fbl depleted Schneider S2 cells; 4) dPANK/fbl depleted Schneider S2 cells treated with pantethine (Siudeja & Seinen
et. al manuscript in prep.). This analysis provides a unique opportunity to identify genes that do respond to the absence of dPANK/fbl protein in the background of normal CoA levels (compare 1 and 4). In other words, this analysis might unravel potential moonlight function of dPANK/fbl.

Interestingly, genetic mapping of the PANK2 mutations in PKAN patients revealed that many (approximately 30%) disease-associated mutations in PANK2 do not affect the mitochondrial localization of PANK2 or the activity or stability of PANK2 [28, 29]. This finding indicates the existence of a non-enzymatic function of PANK2. Alterations of this non-enzymatic function thereby can contribute to the pathogenesis of PKAN. Now with a Drosophila model for PKAN, we can address questions such as whether dPANK has a moonlighting function and whether disruption of this function can contribute to PKAN pathogenesis.

Concluding remarks and perspectives

Although patients suffering from a PKAN-like syndrome were already described in 1922, research in PKAN received momentum only in this decade after the discovery of the causative gene, PANK2 [30]. PKAN research resulted in establishment of different models such as cell models, various mouse models and a Drosophila model [5, 31, 32]. These models are essential to understand the complex pathogenesis of PKAN and shed novel light on the cellular function of PANK protein and the consequences when it is impaired [2, 3, 5, 31-33]. Moreover, these models can also be used to screen for novel compounds, which might alleviate symptoms caused by the loss of PANK. Studies in mice and Drosophila suggest that a major part of the PKAN pathogenesis is due to reduced levels of CoA. Pantethine is a potential compound, which can rescue CoA levels and alleviates most of the disease related symptoms in the Drosophila model. Future studies must be directed towards investigating the potential of pantethine to treat PKAN. Identification of the so far elusive pantetheine kinase (Kinase X, Figure 2) that can generate 4’phosphopantetheine from pantetheine will further enhance our understanding regarding the non-canonical de novo CoA biosynthesis route. This might also be useful in designing more effective/potential treatment strategies regarding the usage of pantethine in PKAN treatment. Our study also surmises a possible moonlight function of PANK, which might unravel a completely new function of PANK and its role in PKAN pathogenesis.

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