REVIEW

This paper is dedicated to the 70th anniversary of the founding of Physiologia Bohemoslovaca (currently Physiological Research)

Coenzyme Q₁₀ Effects in Neurological Diseases

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Summary
Coenzyme Q₁₀ (CoQ₁₀), a lipophilic substituted benzoquinone, is present in animal and plant cells. It is endogenously synthesized in every cell and involved in a variety of cellular processes. CoQ₁₀ is an obligatory component of the respiratory chain in inner mitochondrial membrane. In addition, the presence of CoQ₁₀ in all cellular membranes and in blood. It is the only endogenous lipid antioxidant. Moreover, it is an essential factor for uncoupling protein and controls the permeability transition pore in mitochondria. It also participates in extramitochondrial electron transport and controls membrane physicochemical properties. CoQ₁₀ effects on gene expression might affect the overall metabolism. Primary changes in the energetic and antioxidant functions can explain its remedial effects. CoQ₁₀ supplementation is safe and well-tolerated, even at high doses. CoQ₁₀ does not cause any serious adverse effects in humans or experimental animals. New preparations of CoQ₁₀ that are less hydrophobic and structural derivatives, like idebenone and MitoQ, are being developed to increase absorption and tissue distribution. The review aims to summarize clinical and experimental effects of CoQ₁₀ supplementations in some neurological diseases such as migraine, Parkinson’s disease, Huntington’s disease, Alzheimer’s disease or multiple sclerosis. Cardiovascular hypertension was included because of its central mechanisms controlling blood pressure in the brainstem rostral ventrolateral medulla and hypothalamic paraventricular nucleus. In conclusion, it seems reasonable to recommend CoQ₁₀ as adjunct to conventional therapy in some cases. However, sometimes CoQ₁₀ supplementations are more efficient in animal models of diseases than in human patients (e.g. Parkinson’s disease) or rather vague (e.g. Friedreich’s ataxia or amyotrophic lateral sclerosis).

Key words
Idebenone • MitoQ • Migraine • Parkinson’s disease • Alzheimer’s disease • Multiple sclerosis • Hypertension

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Introduction
Coenzyme Q (CoQ), a highly hydrophobic molecule, is known from 1957 when it was isolated from beef heart mitochondria by Professor Frederick Crane on Madison University (Crane et al. 1957, Crane 1989). CoQ is composed of a benzoquinone ring and a polyisoprenoid lipid tail containing varying chain length depending on the species (Fig. 1). Human isoform contains ten isoprene units (CoQ₁₀) but rodents have mainly nine units (CoQ₉) besides some amount of CoQ₁₀. Briefly, the benzoquinone ring is derived from the essential amino acid phenylalanine, which is converted into tyrosine and then 4-hydroxybenzoate. The polyisoprenoid lipid tail subunits are generated from acetyl-CoA (and through joint intermediate of cholesterol – farnesyl-pyrophosphate) by the mevalonate pathway. The last phase of a CoQ biosynthesis is the condensation of the benzoquinone ring and the polyisoprenoid tail. A lot of knowledge on CoQ biosynthesis originated from experiments on simple organisms such as the budding yeast Saccharomyces cerevisia, fission yeast Schizosaccharomyces pombe or coliform bacterium.

CoQ is present in most aerobic organisms, all animal and plant organs (Battino et al. 1990, Elmberger et al. 1987, Ramasarma 1985). It is endogenously produced in every cell and its intracellular synthesis is its major source, although a small proportion is acquired through the diet. Meat, fish, nuts, and some oils are the richest nutritional sources of CoQ, while much lower levels can be found in most dairy products, vegetables, fruits, and cereals (Cabrini et al. 2008, Mattila and Kumpulainen 2001, Weber 2007, Pravst et al. 2010, Pyo 2010). Interestingly, the daily intake in different countries is very similar and represents around 3-5 mg (Kubo et al. 2007, Pravst et al. 2010, Pyo 2010).

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CoQ concentrations are modified in humans and rats during lifespan (Beyer et al. 1985, Kalén et al. 1989, Zhang et al. 1996). Although the results of the various studies are not in total agreement, generally, in the early phase of life, CoQ concentrations increase, whereas during aging they decrease. Wada et al. (2007) demonstrated that not only the amount of CoQ but also its redox status is essential to balance the oxidative stress associated with the aging process. CoQ concentrations also decrease in mice and pigs with the age. Similarly, an oxidized form of CoQ10 increases indicating higher oxidative stress or a decreased anti-oxidative capacity of aged animals (Onur et al. 2014). Battino et al. (1995) described in rats that CoQ9 and CoQ10 contents in different mitochondrial fractions (synaptic and non-synaptic) are slowly decreasing in three brain areas (cortex, striatum and hippocampus), reaching their minimum in age of 18 months, then increased in the older rats. Nevertheless, the CoQ9/CoQ10 ratio remained constant during aging.

Apart from the earlier study by Kalén et al. (1989) there are few recent human trials. A large cohort of 860 European adults aged 18-82 years shows a decrease of CoQ10 blood concentrations with a shift in redox status in favour of the oxidized fraction in old people of both sexes (Nicklowitz et al. 2016). The recent study on Japanese centenarians (25 males and 74 females) compared to 76-year-old controls confirms decreased serum total levels of CoQ10 significantly shifted to the oxidized form (Nagase et al. 2018). Thus, exogenous CoQ10 supplementation may show benefits as an antiaging agent during aging process.

Subjects are not generally dependent on exogenous supplies of CoQ10. However, apart ageing CoQ10 concentrations are also affected during different pathological disorders. Under these circumstances, dietary supplementation may be needed and would fulfill important functions by counteracting CoQ10 depletion. Most of the clinical work with CoQ10 is focused on the wide spectrum of heart diseases such as ischemic heart disease, congestive heart failure or different cardiomyopathies (Rauchová and Vokurková 2009).

In this short review I have attempted to show the changes of CoQ10 content in different diseases and possible brain effects of the treatment with CoQ10 (and its derivatives) supplementation. This review is focused on CoQ10 applications in CoQ10 deficiency, very frequent type of headache – migraine – and other nervous diseases (Parkinson’s disease, Alzheimer’s diseases, Friedreich’s ataxia or Huntington disease, amyloid lateral sclerosis, sclerosis multiplex) and improvement in noise-induced hearing loss or in cardiovascular hypertension control.

**Multiple functions of coenzyme Q**

CoQ, also known as ubiquinone, acts as a mobile electron and proton transporter from complex I (NADH:
ubiquinone reductase) and complex II (succinate: ubiquinone cytochrome c oxidase) in the inner mitochondrial membrane (Trumpower 1981). The subcellular distribution shows that the inner mitochondrial membrane has the largest portion of CoQ. In comparison with other respiratory carriers the content of CoQ exceeds other redox components by about tenfold (Capaldi 1982). Moreover, CoQ accepts electrons from other dehydrogenases, which are present in lower amounts, and seems to be rate-limiting in the integrated electron transfer (Genova and Lenaz 2011, 2014). Among them localized on the outer surface of the inner membrane there is mitochondrial FAD-linked glycerol-3-phosphate dehydrogenase – the simplest branch of the respiratory chain and a part of glycerol-3-phosphate shuttle (Rauchová et al. 1992, Rauchová et al. 1997). CoQ is also an obligatory cofactor for FMN-linked dihydroorotate dehydrogenase – a key enzyme of de novo pyrimidine biosynthesis, which is loosely associated with the outer surface of the inner membrane (Evans and Guy 2004, Reis et al. 2017). On the matrix side of inner membrane there is electron transport flavoprotein dehydrogenase forming a short pathway that transfer electron from 11 different mitochondrial flavoprotein dehydrogenases to the quinone pool – an essential enzyme involved in the fatty acid β-oxidation and branched-chain amino acid oxidation pathways (Freeman 1988, Watmough and Freeman 2010). Further there are FAD-dependent proline dehydrogenase (an enzyme required for proline and arginine metabolism) and sulphide-quinone oxidoreductase (Blake et al. 1976, Quinzii et al. 2017). Fig. 2 shows a schematic illustration of the CoQ integration in the mammalian mitochondrial respiratory chain.

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![Fig. 2. A schematic illustration of CoQ₁₀ integration in the mammalian mitochondrial respiratory chain. Electrons (e⁻) accept oxidized form of coenzyme Q₁₀ (CoQ₁₀) from complex I (C I) and complex II (C II), mitochondrial glycerol-3-phosphate dehydrogenase (GPDH), dihydroorotate dehydrogenase (DHODH), electron transport flavoprotein dehydrogenase (ETFDH), proline dehydrogenase (ProDH) and sulfide dehydrogenase (SulDH) for delivery to complex III (C III) and finally to complex IV (C IV). Glycerol-3-phosphate (GP), dihydroxyacetone phosphate (DHAP), dihydroorotate (DHO), orotate (ORO), cytochrome c (Cyt c) and pyrroline-5-carboxylate.](image-url)
Safety and bioavailability of coenzyme Q10

As a natural component, CoQ10 is well tolerated. However, its therapeutic applications are greatly limited because CoQ10 is almost insoluble in water (due to its high hydrophobicity) and has relatively large molecular mass (863.34 g/mol). In rats, only about 2-4 % of orally administered CoQ10 could be absorbed (Zhang et al. 1995). Divided dosages (2 x100 mg) produce a larger increase in plasma levels than a single peroral 200 mg dose (Singh et al. 2005). Hence, large daily doses are recommended to be divided into several doses to maximize the CoQ10 absorption. To improve its solubility and bioavailability, several advancements have been made and a variety of preparations has been developed such as compressed tablets, chewable tablets, powder-filled capsules or soft gels containing a suspension in oil (Bhagavan and Chopra 2007). Very recent papers summarize data about various preparations of CoQ10 with improved solubility and biological availability (Ehrenhaus Masotta et al. 2020, Pastor-Maldonado et al. 2020, Pravst et al. 2020, Takahashi and Takahashi 2019). Water-soluble CoQ10 that improves the bioavailability of natural CoQ10 is non-toxic and stable over long periods of time Ubisol-Q10 prepared by method using polyethylene glycol-derivatised natural compounds (Borowy-Borowski et al. 2004).

Orally administered CoQ10 is absorbed from the gastrointestinal tract (GIT) similarly as vitamin E or different lipid soluble substances (Bhagavan and Chopra 2007). The data disclosed regional differences in permeability throughout the GIT (Palamakula et al. 2005). The maximum permeability occurred in the duodenum pointing at the peculiar expression of transporters along the GIT. The second most favorable region for absorption was the colon followed by the jejunum and stomach. After the absorption in GIT, CoQ10 is reduced and transported to the liver, where it is incorporated into chylomicrons. In the circulation CoQ10 is transported as very low-density lipoprotein (VLDL) or low-density lipoprotein (LDL) particles. After oral administration, the maximum plasma CoQ10 concentration occurs at 6 to 8 hours (Bhagavan and Chopra 2006). Ochiai et al. (2007) found that intestinal absorption of CoQ10 after administration of the emulsion formulation of CoQ10 was also enhanced by food intake in Wistar rats: intestinal absorption was three times faster with food intake. However, the large interindividual variations following the CoQ10 administration were

Beyond fundamental role of an electron carrier associated with cellular energy production in the respiratory chain, CoQ functions as a principal cofactor in the activation of protein uncoupling (Echtay et al. 2000) and it controls permeability of transition pores (Fontaine et al. 1998, Walter et al. 2002). However, CoQ occurs in other cellular membranes such as Golgi apparatus, lysosomes or plasma membrane having a role in functioning of oxido-reductase systems. Gille and Nohl (2000) described the lysosomal membrane redox chain, which provides the low pH inside the organel for the best functioning hydrolytic enzymes necessary for the removal of useless proteins. Moreover, CoQ can also change membrane stability or fluidity what could be important for physiological functions of receptors, carriers and membrane-bound enzymes (Agmo Hernández et al. 2015, Fato et al. 1984). The bioinformatic analyses show that CoQ affects the expression of many genes involved in different cellular pathways (Schmelzer et al. 2007).

In addition, CoQ turns between fully oxidized form, quinone, – through a formation of its semiquinone – and fully reduced form (Fig. 1). The reduced form, ubiquinol, functions as a potent antioxidant and free radical scavenger by either directly scavenging free radicals or recycling and regenerating other antioxidants such as tocopherol (vitamin E) and ascorbic acid (vitamin C). So, by this way it protects membrane lipids, proteins and mitochondrial DNA against oxidative damage. CoQ represents the only lipid soluble antioxidant synthesized by own cells. On the other hand, oxido-reduction character of CoQ has also the important prooxidant role for the formation of superoxide anion (O$_2^-$) and hydrogen peroxide (H$_2$O$_2$) in cell signaling systems (Linnane et al. 2007). Furthermore, CoQ acts as a regulator of cell growth and differentiation and a blocker of apoptosis (Kagan et al. 1999, Li et al. 2019) and has anti-inflammatory effects (Schmelzer et al. 2007, Schmelzer et al. 2008). Systematic reviews evaluated the effects of CoQ10 supplementation on various inflammatory markers including C-reactive protein, interleukin-6 or tumor necrosis factor-α (Fan et al. 2017, Zhai et al. 2017).

The functional diversity reflects a suitability of CoQ for applications in clinical studies as an alternative medication or dietary supplement for several diseases, which also includes neurological disorders.
demonstrated. Mantle and Dybring (2020) summarized that the relative bioavailability and efficacy of administered oxidized and reduced forms of CoQ_{10} seems to be similar. Moreover, various cell types lining the GIT may have a capacity to reduce CoQ_{10} and facilitate its conversion. Evidence from pharmacokinetic studies suggest that exogenous supplementation of CoQ_{10} does not influence the biosynthesis of endogenous CoQ_{9}/CoQ_{10} nor does it accumulate in plasma or tissues after the cessation of supplementation (Hidaka et al. 2008).

As concerns CoQ_{10} crossing brain capillary endothelial cells i.e. the blood-brain barrier (BBB) Matthews et al. (1998) showed that oral administration of CoQ_{10} (200 mg/kg/day for two months) increased both brain and brain mitochondrial concentrations in 12- and 24-month-old male Sprague-Dawley or 24-month-old Fisher 344 rats. Kwong et al. (2002) reported small but significant increase in brain mitochondria in 14-month-old male Sprague-Dawley for 13 weeks feeding (150 mg/kg/day). Smith et al. (2006) used high doses (1,000-5,000 mg/kg/day) of CoQ_{10} in the R6/2 transgenic mouse model of Huntington’s disease and significantly increased plasma and brain levels of CoQ_{10} and CoQ_{9}. Kanzalov et al. (2003) found significantly elevated CoQ_{10} in brain mitochondria but not in the brain homogenate in male mouse C57B1 for 11 weeks feeding. On the other hand, other reports show no increase of CoQ_{10} with oral administration in 3-month-old or 24-month-old male Sprague-Dawley for 13 weeks feeding.

CoQ_{10} (30 mg/kg) crossed BBB of adult male Wistar rats and accumulated in the brain when administered intravenously (Belousova et al. 2016). A single intravenous injection of CoQ_{10} in the rat model of transient focal ischemia led to a 67 % reduction in brain lesion size 24 hours after CoQ_{10} administration and although the infarct had increased by 7 days, it remained smaller than that of saline-treated rats (Belousova et al. 2016). Recently, Wainwright et al. (2020) investigated mechanisms of CoQ_{10} transport across the BBB, using normal and pathophysiological (CoQ_{10}-deficient) cell culture models and identified lipoprotein-associated uptake and efflux mechanisms regulating CoQ_{10} transfer. They showed that there is a dynamic interplay of multiple transport receptors with varying degrees of influence. They brought a substantial evidence for the involvement of receptor for advanced glycation endproducts, low density lipoprotein receptor and scavenger receptor in the transport of exogenous CoQ_{10} into brain.

CoQ_{10} is well tolerated and safe. Data from experimental and clinical studies indicated repeatedly that CoQ_{10} is highly safe for the use as a dietary supplement compared with placebo group (Ferrante et al. 2005, Huntington Study Group Pre2CARE Investigators et al. 2010, Kitano et al. 2008, Liu and Artmann 2009, Zhu et al. 2017). Kitano et al. (2008) evaluated the potential subchronic toxicity of reduced and oxidized CoQ_{10} orally administered to Sprague-Dawley rats (rodents with the primary form of CoQ_{9}) and beagle dogs (mammals with the primary form of CoQ_{10}). The authors observed no adverse effects in male or female rats administered 600 and 200 mg/kg/day, respectively. In the dog study, the highest dose tested (600 mg/kg/day) indicated no adverse effects in males and females. The observed safe level risk assessment method indicated that the evidence of safety is strong at intakes up to 1,200 mg/day (Hathcock and Shao 2006, Ikematsu et al. 2006). Nevertheless, even a daily dosage up to 3,600 mg was found to be tolerated by healthy as well as unhealthy persons (Huntington Study Group Pre2CARE Investigators et al. 2010). In general, CoQ_{10} shows only a low incidence of adverse events: dizziness, nausea/vomiting, heartburn, stomach upset or related mild and transient gastrointestinal effects (Hathcock and Shao 2006, Raizner 2019).

It should be noted that CoQ_{10} is not approved by the US Food and Drug Administration for treatment of any medical condition (Raizner 2019). It is sold as a food additive, not as drugs, and its manufacturing is not regulated in the same way as drugs. The European Medicine Agency approved ubiquinol ─ the reduced form of CoQ_{10} ─ as an orphan drug for the treatment of primary CoQ_{10} deficiency in 2016. According to my knowledge, Myoquinon (Pharma Nord ApS) is approved for medical treatment of proven CoQ_{10} deficiency or adjunctive therapy to relieve symptoms of chronic heart failure in Hungary.

**Coenzyme Q_{10} analogues**

A synthetic short-chain analogue of CoQ_{10} idebenone (hydroxydecylubiquinone, IDB) was launched by Japanese Takeda Chemical Industries in 1986 (Fig. 3). IDB with a hydroxydecyl side chain (10 carbon atoms) and m.w. 339.44 is less hydrophobic than natural CoQ_{10} with m.w. 863.49 (Zs-Nagy et al. 1990). IDB acts as an electron carrier in the mitochondrial electron transport chain but it inhibits complex I ─ NADH dehydrogenase (Esposti et al. 1996, Rauchová et al. 2008). On the other
hand, IDB transfers electrons from complex II – succinate dehydrogenase or from glycerol-3-phosphate dehydrogenase to complex III (Brière et al. 2004, Rauchová et al. 2012). Similarly, as CoQ10, IDB acts as a potent antioxidant agent (Lin et al. 2015, Muscoli et al. 2002, Rauchová et al. 2006). IDB is well-tolerated in experiments and clinical trials, e.g. for patients with Friedreich’s ataxia, Huntington’s disease, Alzheimer’s disease, multiple sclerosis etc. (Jaber and Polster 2015). To improve IDB effectiveness in the therapeutic treatment, IDB similarly to CoQ10 can be incorporated in liposomes, cyclodextrins or nanoparticles (Montenegro et al. 2018). Gueven et al. (2015) compared the structural similarity, pharmacokinetics and modulation of cellular energy production of IDB and natural CoQ10. Consequently, IDB and CoQ10 are unable to substitute for each other. A very recent review of Gueven et al. (2021) summarized that IDB (and its metabolites) protect against the multitude of toxic stimuli. The authors also mentioned some new discoveries e.g., competitive inhibition of p52Shc, retinal expression of the RNA-binding protein Lin28A or impact on inflammation and endoplasmatic reticulum stress. Thus, the effects of IDB cannot be explained only by an antioxidant activity or a normalization of mitochondrial energy supply. It seems more likely that IDB activates one or several essential pathways that explain its broad activity (Gueven et al. 2021). A broad range of IDB activity is very similar to multiple functions of coenzyme Q but the activities might also be different because of different chemical structure.

Mitoquinone (MitoQ) was developed for oxidative stress treatment (James et al. 2005, Smith and Murphy 2010). Structure of MitoQ consists of lipophilic cation — triphenylphosphonium (TPP) attached to ubiquinone head group via a 10-carbon aliphatic chain (Fig. 4). MitoQ crosses easily through all biological membranes, including the blood-brain barrier and neuronal membranes. MitoQ concentrates hundredfolds in mitochondria driven by high membrane potential across the inner mitochondrial membrane. Oral delivery of MitoQ protects mitochondria from damage and may therefore form the basis for mitochondria-protective therapies (Murphy and Smith 2007). It was shown that MitoQ had a protective role in animal and cell models of several human disease, including Parkinson’s disease, Alzheimer’s disease or sclerosis multiplex.
CoQ₁₀ deficiency

Primary CoQ₁₀ deficiency, which can cause reduced levels of CoQ₁₀ in tissues, includes mutations in the genes participating in the complicated biosynthesis of CoQ₁₀, as described by Mollet et al. (2007), Ogashara et al. (1989), Quinzii et al. (2006), Rötig et al. (2000) and others. In many cases the family history suggests an autosomal recessive mode of inheritance. Alzár-Fabra et al. (2018) presented the updated comprehensive review of the very heterogeneous clinical spectrum associated with primary CoQ₁₀ deficiency. At present 10 genes encoding biosynthesis of CoQ₁₀ have their pathogenic variants bringing about human CoQ₁₀ deficiency (Alzár-Fabra et al. 2018). Besides of cardiac, muscular and renal manifestations the peripheral and central nervous system is often affected including encephalopathy, seizures, cerebellar ataxia, epilepsy, sensorineural hearing loss, optic atrophy or intellectual disability in these patients.

Primary CoQ₁₀ deficiency is very rare (Yu et al. 2019). Much more frequent secondary CoQ₁₀ deficiency includes the defects not directly connected with biosynthesis of CoQ₁₀ (Alzár-Fabra et al. 2018, Desbats et al. 2015, Yubero et al. 2016). Many reports focus on skeletal muscle and central nervous system. Muscular manifestations consist of weakness, hypotonia, exercise intolerance and myoglobinuria, while the main CNS manifestations include ataxia and general CNS impairment (Desbats et al. 2015).

CoQ₁₀ supplementation can be effective for treatment of both primary and secondary CoQ₁₀ deficiencies (Potgieter et al. 2013). Duberley et al. (2014) evaluated the effect of CoQ₁₀ supplementation on the well-established neuronal model of CoQ₁₀ deficiency. Human SH-SY5Y neuronal cells with 1 mM competitive inhibitor of mammalian CoQ biosynthesis in cell cultures — para-aminobenzoic acid — induced approximately a half decrease of cellular CoQ₁₀ concentration accompanying by a fourfold increase in mitochondrial oxidative stress and global loss of mitochondrial respiratory chain enzyme activities. Following CoQ₁₀ supplementation for 5 days there was a markedly increased cellular CoQ₁₀ status. CoQ₁₀ treatment (2.5 μM) significantly decreased the level of mitochondrial superoxide in the CoQ₁₀-deficient neurons. CoQ₁₀ treatment (5 μM) restored mitochondrial membrane potential to 90 % of the control level. However, CoQ₁₀ treatment (10 μM) was only partially effective in restoring enzyme activities of mitochondrial respiratory chain. This study indicated that although mitochondrial oxidative stress can be attenuated in CoQ₁₀-deficient neurons following CoQ₁₀ supplementation, mitochondrial respiratory chain enzyme activities appear to be partially refractory to this treatment. The therapy with >10 μM CoQ₁₀ may be required to restore mitochondrial respiratory chain enzyme activities to the control level.

Very important for the treatment of primary or secondary CoQ₁₀ deficiency is early identification and early supplementation to omit irreversible damages in the central nervous system (and other organs).

Migraine

Migraine is a debilitating condition characterized by headaches and nausea with a usual onset around puberty. Associated symptoms may be sensitivity to light, sound or smell and vomiting. Migraine affects 10 % people worldwide and it is approximately three times more common in women than in men (Vos et al. 2012, Woldeamanuel and Cowan 2017). Although migraine ranks among the most frequent neurological disorders, its pathophysiology remains not fully understood. Mitochondria and energetic metabolism have long been postulated to be involved in the etiology of migraines, although a direct link has been difficult to identify (Sparaco et al. 2006, Yorns and Hardison 2013).

A small open-label study with 32 adults showed some effectiveness of 150 mg of CoQ₁₀ supplementation as a preventive treatment for migraine headaches (Rozen et al. 2002). The other (double-blind, randomized, placebo-controlled) study with 42 adult migraine patients used CoQ₁₀ supplementation (3x100 mg/day). CoQ₁₀ was superior to placebo for attack frequency, headache-days and days-with-nausea in the third treatment month (Sándor et al. 2005).

Hershey et al. (2007) found that deficiency of CoQ₁₀ may be quite common in pediatric and adolescent migraine. They measured plasma CoQ₁₀ in 1550 patients (aged 13 to 22 years). Consequent CoQ₁₀ supplementation in patients with low plasma CoQ₁₀ (1 to 3 mg/kg/day of CoQ₁₀ in liquid gel capsule formulation) resulted in clinical improvement. In a double-blinded, placebo-controlled study with 120 pediatric and adolescent migraine receiving 100 mg CoQ₁₀ supplementation for 32 weeks, the improvement was seen in weeks 1-4 but there was no difference in headache outcomes between the CoQ₁₀ supplementation and
placebo in week 32 (Slater et al. 2011). CoQ10 supplementation (400 mg/day per 3 months together with prophylactic medication) showed significant improvement in frequency, severity and duration of migraine attacks in CoQ10 group compared to placebo in 45 women aged 18-50 years. Interestingly, the levels of inflammatory marker tumor necrosis factor-α (TNF-α) were reduced significantly but interleukin IL-6 and IL-10 levels were not affected (Dahri et al. 2019).

Recently, Zeng et al. (2019) included five studies from 2002-2018 with 346 patients (120 pediatric and 226 adult subjects) in the meta-analysis. CoQ10 was comparable with placebo in respect to migraine attacks/month and migraine severity/day. However, CoQ10 was more effective than placebo in reducing migraine days/month and migraine duration. Another recent meta-analysis included four studies from 2005-2018 with 221 patients (Parohan et al. 2020). They concluded that the greatest impact of CoQ10 supplementation was on the frequency of attacks per month without affecting the severity or duration of migraine attacks.

In addition to CoQ10 several other nutraceuticals have been demonstrated to have potential effectiveness for migraine prevention such as magnesium, riboflavin, carnitine or herbal remedies and their different combinations together with aerobic exercise or other forms of relaxation training, cognitive therapies and acupuncture (Mauskop 2012). A double-blind, placebo-controlled study with 130 adult patients (18-65 years) evaluated the efficacy of a proprietary supplement containing magnesium, riboflavin and Q10 (commercially available food supplement Migravent® in Germany or Dolovent® in USA) (Gaul et al. 2015). After three months of treatment with this supplement, a pain and burden of migraine were statistically significantly reduced compared to placebo patients, but it did not show statistically significant efficacy on migraine frequency. Results with another proprietary supplement containing feverfew (Tanacetum parthenium), CoQ10 and magnesium (Antemig® in France since 2014) could be beneficial and safe for the prevention of migraine in adult patients (Guilbot et al. 2017). A double-blind 8-week lasting study with concurrent CoQ10 (30 mg/day) and carnitine (500 mg/day) supplementation provided the evidence supporting some beneficial effects on mitochondrial metabolism (decrease of lactate serum level) and migraine symptoms (Hajijashemi et al. 2019). Parohan et al. (2021) reported a synergistic effect of nano-curcumin and CoQ10 (300 mg/day) given for 8 weeks in a double-blind, placebo-controlled study with 91 adult patients.

**Parkinson´s disease**

Parkinson’s disease (PD) is one of the most common neurodegenerative diseases with still unknown primary cause. There is a long-term degenerative disorder of the central nervous system that mainly affects the motor system and affects about 1-2 % of the elderly population with usual onset over 60. It is prevalent in males. The most obvious symptoms are shaking (due to decrease in dopaminergic modulation of the substantia nigra pars compacta neurons altering motor systems), rigidity, slowness of movement and difficulty with walking. Inclusions of Lewy bodies in midbrain and presence of immunoreactive α-synuclein and ubiquitin on autopsy are hallmarks of the disease (Oertel and Schulz 2016, Stanga et al. 2020). Mitochondrial dysfunction contributes significantly to neuronal loss in PD (McCoy and Cookson 2012, Stanga et al. 2020). Mitochondria of patients have decreased complex I activity not only in substantia nigra (Schapira et al. 1990a, b), striatum (Mizuno et al. 1989) and frontal cortex (Parker et al. 2008) but also in skeletal muscle (Bindoff et al. 1991) or platelets (Haas et al. 1995, Krige et al. 1992). The other study found significant deficiency of CoQ10 in cortex but not in substantia nigra, striatum or cerebellum in brains samples of PD patients (Hargreaves et al. 2008). Studies also reported deficiency of CoQ10 platelets (Krige et al. 1992, Shults et al. 1997). Functional intracellular assay (FIA) methodology analyzing blood samples also assessed CoQ10 deficiency in patients with PD compared to age- and gender-matched controls (Mischley et al. 2012). In addition, their mitochondria show oxidative stress, disturbance in calcium homeostasis, impaired clearance of dysfunctional mitochondria, changes in mitochondrial biogenesis and the loss of membrane potential (McCoy and Cookson 2012).

Inhibitors of mitochondrial complex I of the oxidative phosphorylation pathway induce degeneration of dopaminergic neurotransmission in rodents and several other animal models of PD (Hamadjida et al. 2019, Tieu 2011). The most often used chemicals are MPTP, 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (Beal et al. 1998, Jackson-Lewis and Przedborski 2007, Przedborski et al. 2004), nonselective herbicide paraquat (PQ), N,N'-dimethyl-4,4'-bipiridinium (Cicchetti et al. 2005,
McCarthy et al. 2004), or botanical insecticide and nonselective piscicide rotenone (Caboni et al. 2004, Cannon et al. 2009, Sherer et al. 2003). Many scientists found some benefit of CoQ10 supplementation in the above-mentioned experimental animal models of PD. Cleren et al. (2008) showed significant neuroprotective effects of CoQ10 against acute treatment with MPTP, which produced severe dopamine depletion in 5-month-old male mice. Transgenic mice with DJ-1 (Parkinson disease protein 7) deficiency (DJ-1/PARK7) with the hypersensitivity to MPTP showed a clear neuroprotection by a prophylactic use of Ubisol-Q10, water-soluble nanomicellar formulation of CoQ10 (Muthukumaran et al. 2014b). Attia and Maklad (2018) indicated that CoQ10 supplement (200 mg/kg) caused a remarkable improvement in most of the behavioral tests and decreased protein carbonyl content in the brain in mouse PQ model, particularly when treatment of CoQ10 started prior rather than after PQ induction of PD. Ubisol-Q10 given in drinking solution (12 mg/kg/day) was effective in blocking the progression of neurodegeneration in PQ rat model when administered therapeutically (after PQ injection) (Muthukumaran et al. 2014a). However, Ubisol-Q10 must be given continuously and cannot be withdrawn in order to continue neuroprotection. The withdrawal led to further neurodegeneration. The authors suppose that Ubisol-Q10 halts neurodegeneration by supporting of remaining neurons (Muthukumaran et al. 2014a).

Furthermore, there are also cellular models, which develop pathology more quickly, do not require ethical approval and are less costly (Falkenburger et al. 2016). Treatment with water-soluble CoQ10 was successful in human neuroblastoma (SH-SY5Y) cells paraquat model of PD (i.e. 10 μM paraquat in complete media for 48 hours at 37 °C), where it inhibited reactive oxygen species generation, reduced the number of apoptotic cells and DNA fragmentation (McCarthy et al. 2004). Another in vitro PD model of SH-SY5Y cells involved the addition of 6-hydroxydopamine (6-OHDA). 6-OHDA did not induce extensive oxidative damage of mitochondria but only a mild redox signal, which activated the machinery of mitochondrial fission and disrupted the mitochondrial morphology (Solesio et al. 2013). Treatment with mitochondria-targeted antioxidant MitoQ hand, IDB transfers electrons from complex II–succinate through its capacity to alter mitochondrial redox processes hand, IDB transfers electrons from complex II–succinate inhibited the migration of cytosolic dynamin-related protein-1 (Drp1) and pro-apoptotic protein Bax to the mitochondria and reduced the mitochondrial morphology alterations induced by 6-OHDA (Solesio et al. 2013). Xi et al. (2018) confirmed the protective effects of MitoQ on mitochondrial dynamics in 6-OHDA-induced in vitro (SN4741 cells derived from substantia nigra of mouse embryos) and in vivo models of PD (adult C57bl/6 male mice).

However, there are differences in the pathogenesis of the PD models and of human PD. PD models acts on complex I through a competitive inhibitory process for which CoQ10 supplementation is beneficial. The idea that supplementation of CoQ10 could retard the rate of PD progression of patients is rather old (Müller et al. 2003, Shults et al. 2002, Strijks et al. 1997, Yoritaka et al. 2015). Strijks et al. (1997) did not notice any beneficial effect in 10 patients treated with 200 mg of CoQ10 for 3 months. Shults et al. (2002) used three dosage of CoQ10 (300, 600 and 1200 mg/day) in 80 subjects with early PD for 16 months. The patients developed less disability, and the benefit was greatest in subjects receiving the highest dosage. Müller et al. (2003) indicated a moderate beneficial effect in PD patients (seven males and seven females) after oral application of 360 mg of CoQ10 lasting 4 weeks. Yoritaka et al. (2015) also indicated benefit for Japanese PD patients, who took 300 mg ubiquinol-10 capsules for 96 weeks. The reason can be that not all PD patients have low serum CoQ10 levels. Jiménez-Jiménez et al. (2000) found similar serum CoQ10 levels in 33 PD patients and 31 matched controls. However, earlier report showed decreased serum CoQ10 levels in PD patients (Matsubara et al. 1991).

Unfortunately, recent reviews and meta-analysis disclose that CoQ10 supplement plays only a limited role in the treatment of PD. It does not slow functional decline nor provides any symptomatic benefit for patients with PD (Negida et al. 2016, Oertel and Schulz 2016, Parkinson Study Group QE3 et al. 2014, Zhu et al. 2017).

**Huntington's disease**

Huntington's disease (HD), also known as Huntington's chorea or Saint Vitus' dance, is a rare autosomal dominant inherited neurodegenerative disease with the origin of symptoms at the age of 30-50 years. HD is characterized by progressive motor, behavioral and cognitive decline, resulting in death within 15 to 20 years after the diagnosis for which there is no effective therapy. The genetic defect of HD is caused by cytosine-adenine-
guanine (CAG) trinucleotide expansion in the huntingtin gene resulting in the production of an expanded polyglutamine in the mutant huntingtin protein. The cure is based largely on symptomatic treatment and lifestyle interventions with supportive management (Kumar et al. 2020, Yu and Bega 2019).

Mitochondria and energetic metabolism dysfunction as well as oxidative stress contribute to the neurodegenerative process (Koroshetz et al. 1997, Tobore 2019). However, antioxidant treatment with CoQ10 and vitamin E was not very successful in HD models. Combined administration (250 mg CoQ10 + 530 mg vitamin E/kg/day) could not prevent the decline of brain respiratory chain function in the HD model of Wistar rats injected with 3-nitropropionic acid (Kasparová et al. 2006). Combined supplementation did not also increase survival rates and pupal mortality of flies in the HD model of Drosophila melanogaster (Bahadorani and Hilliker 2008). It seems that antioxidants alone are not enough to delay or to stop the progress of HD. Two recent extensive reviews tried to answer the questions connected with the role of antioxidants and their therapeutic possibilities in HD (Bono-Yagüe et al. 2012, Essa et al. 2019).

Ranen et al. (1996) undertook a one-year, placebo-controlled, double-blind study with IDB. They did not find any significant differences between 91 patients receiving synthetic analogue of CoQ10 IDB (90 mg/day) or placebo group. The next placebo-controlled 30-month-trial tried to assess the impact of CoQ10 (300 mg twice daily) and a noncompetitive glutamatergic NMDA (N-methyl D-aspartate) receptor antagonist, remacemide hydrochloride (200 mg three times daily) but neither CoQ10 nor remacemide produced significant slowing in functional decline in early HD patients (Huntington study group 2001). On the other hand, several studies report beneficial effects of CoQ10 on behavior and pathology in mouse models of HD. The transgenic HD mice (R6/2) are widely used as a fast-progressing model in trials testing potential therapies. R6/2 mice with oral administration of CoQ10 or remacemide significantly increased survival and delayed the development of many HD symptoms. Combined treatment (CoQ10+remacemide) was even more efficient (Ferrante et al. 2002). The authors suggest several potential explanations for the observed discrepancy: the dose of remacemide was 2.5-fold higher in mice, the pathophysiology of neurodegeneration in the transgenic mice may not be entirely reminiscent of that occurring in human patients and the disease stage in which the therapeutic trials were initiated was markedly different (Ferrante et al. 2002). Schilling et al. (2001) also found the amelioration of motor deficit but no prolonged survival of transgenic HD-N171-82Q mice after a combined treatment (CoQ10+remacemide). Combined tetracycline antibiotic with antimicrobial and antiinflammatory properties minocycline and CoQ10 treatment provided an amelioration of behavior and neuropathological alterations (Stack et al. 2006). Moreover, this therapy improved motor performance to a greater degree than either minocycline or CoQ10 alone and significantly extended the survival of the R6/2 mice. In addition, combined minocycline and CoQ10 treatment attenuated gross brain atrophy, striatal neuron atrophy and specific protein huntingtin aggregation relative to the treatment with other drugs. However, Menalled et al. (2010) did not confirm the previously reported benefits. They found that neither CoQ10 nor minocycline caused significant improvements on measures of motor function or general health, e.g. open field, rotarod, grip strength, rearing-climbing, body weight and survival in the R6/2 mouse model. The authors discuss possible reasons of discrepancies, such as different founder lines of R2/6 mice, effect of nutrition and husbandry or number of experimental animals and behavior tests used. On the other hand, Hickey et al. (2012) used a slowly progressing HD model, the homozygote mutant CAG140 knock-in mouse, which expresses the full-length protein in the proper genomic context and may better reproduce human pathology. The mice display progressive motor, cognitive and emotional anomalies, transcriptional disturbances and late striatal degeneration. The authors report beneficial effects of 0.2 % CoQ10 in diet on motor behavior. Suprisingly, the lower (0.2 %) dose of CoQ10 was more effective than the higher (0.6 %) dose. The data emphasize that maximum benefit may be observed when treatment is begun at early stages of the disease, when neuropathological changes are minimal. It can explain the different results between Menalled et al. (2010) using the more rapid R6/2 mouse model and Hickey et al. (2012) who studied a slowly progressing CAG140 knock-in mouse model.

Another combined therapy (with creatine) produced additive neuroprotective effects, such as improving of motor performance and survival extension, in R6/2 transgenic mouse model of HD (Yang et al. 2009). Smith et al. (2006) performed a study administering high levels of CoQ10 to R6/2 transgenic
mice (from two different commercial sources). High doses of CoQ₁₀ (1,000, 5,000, 10,000 or 20,000 mg/kg/day significantly extended survival and improved motor performance and grip strength, reduced weight loss and brain atrophy in R6/2 at 90 days.

Unfortunately, a recent multicenter randomized, double-blind study with 609 patients with early stage of HD (from the United States, Canada and Australia) obtaining 2,400 mg per day (or placebo) for 60 months showed no beneficial effect (McGarry et al. 2017). The trial was concluded early on the basis of an interim analysis and futility.

**Alzheimer's disease**

The most common, progressive, irreversible and fatal brain disease is Alzheimer's disease (AD), which disturbs cognition and memory functions. AD is strongly associated with increasing age with usual onset over 65 years old. Globally, the greatest contributors to AD risk are smoking following by diabetes, mid-life hypertension, mid-life obesity, depression and physical inactivity (Barnes and Yaffe 2011). AD affects about 40 million individuals worldwide. AD’s Association reports extensive analysis of information of AD, including incidence and prevalence, mortality rates, health expenditures, cost of care and effect on caregivers and society in general in the United States (Alzheimer’s Association 2013). Unfortunately, the cause of AD is not quite understood, the cure is not known, the prognosis remains poor, and the number of suffering people is increasing what impose an extreme burden to public healthcare systems worldwide. AD is characterized by the presence of pathological features in brain: amyloid-β peptide plaques and neurofibrillary tangles in pyramidal neurons. In addition, AD covers many neuropathologies and pathophysiological processes, such as neuroinflammation (Sochocka et al. 2017), oxidative stress (Atwood et al. 1999), vascular dysfunction (Di Marco et al. 2015), dendritic (Baloyannis 2009) and synaptic pathologies (Manyevitch et al. 2018). Damaged mitochondria also have an important role (Baloyannis 2006, Stanga et al. 2020, Wang et al. 2020). Moreover, Joshi et al. (2015) described Golgi apparatus fragmentation, which results in enhanced amyloid precursor protein and amyloid-β production.

Södeberg et al. (1992) reported increased levels of CoQ₁₀ in postmortem brain samples. In observed brain regions of AD patients such as frontal cortex, precentral cortex, temporal cortex, frontal white matter, nucleus caudatus, hippocampus, pons, cerebellum and medulla oblongata, CoQ₁₀ levels increased significantly compared to the controls, with the elevations varying between 30 and 100%. The elevated levels of CoQ₁₀ may reflect a change in oxidative stress (Södeberg et al. 1992). As concerns on plasma CoQ₁₀, De Bustos et al. (2000) compared serum CoQ₁₀ level and CoQ₁₀/cholesterol ratio in 44 patients with AD, 17 patients with vascular dementia and 21 matched controls and the data were not significantly different. The values did not correlate with age, age at onset, duration of disease or score in cognitive tests. Other study confirmed no significant difference between 42 cognitively intact and 23 AD patients on plasma CoQ₁₀ level (Giavarotti et al. 2013). However, Fišar et al. (2019) revealed an association between plasma CoQ₁₀ concentration and the MMSE score in AD patients. The authors supposed that an even insignificant decrease in plasma CoQ₁₀ concentration might play a role in the cellular dysfunction found in AD patients.

In the nineties, two smaller studies described improvements of memory, attention and behavior after IDB administration (Bergamasco et al. 1994, Senin et al. 1992). Gutzmann and Hadler (1998) conducted the two-year prospective, randomized, double-blind multicentre study with 450 patients with dementia of the AD type of mild to moderate degree. Their results suggested that IDB exerted its beneficial therapeutic effects on the course of the disease by slowing down its progression. However, Thal et al. (2003) in a one-year, multicenter, double-blind, placebo-controlled, randomized trial found that IDB failed to slow cognitive significant decline in 536 patients aged over 50 years with a diagnosis of probable AD and mild to moderate cognitive test (MMSE) scores. Patients were treated with three different doses of IDB 120, 240, or 360 mg three times daily. Galasko et al. (2012) discovered that antioxidants (400 mg of CoQ₁₀ 3 times daily or 800 IU of vitamin E plus 500 mg of vitamin C plus 900 mg of α-lipoic acid daily) for 4 months did not influence cerebrospinal fluid biomarkers related to amyloid or tau pathology of patients with mild to moderate AD.

There are different mice models of AD disease. Yang et al. (2008) tested the effect of CoQ₁₀ on β-amyloid in the 16-month-old transgenic mice overexpressing the Alzheimer presenilin 1-L235P mutation (leucine-to-proline mutation at codon 235). Mice, which were fed with CoQ₁₀ (1,200 mg kg/day) for 60 days, effectively decreased amyloid-β overproduction...
and depressed oxidative stress. Additionally, CoQ10 treatment improved markers of oxidative stress such as downregulation of superoxide dismutase and increased levels of malondialdehyde in transgenic mice relative to the wild-type mice. Another study found that CoQ10 treatment of Tg19995 transgenic mouse model of AD decreased brain levels of protein carbonyls, a marker of oxidative stress, and provided protection against plaques and memory loss, as measured by the Morris water maze testing (Dumont et al. 2011). Transgenic mice with the P301S tau mutation, which causes frontotemporal dementia in man, were fed a control or 0.5 % CoQ10 diet (Elipenahl et al. 2012). The results show that CoQ10 significantly improved behavioral deficits and survival in transgenic mice with the P301S tau mutation. The authors also described a significant increase in mitochondrial complex I activity and protein levels and reduced oxidative stress with a reduction in lipid peroxidation. Muthukumaran et al. (2018) evaluated the neuroprotective effects of water-soluble formulation of CoQ10, Ubisol-Q10 in drinking water (at a dose of 6 mg/kg/day) in one-month-old double transgenic male AD mice containing human/mouse chimeric amyloid β precursor and a mutant presenilin-1 gene. Ubisol-Q10 treatment reduced circulating amyloid peptide, improved long term memory, preserved working spatial memory and drastically inhibited amyloid plaque formation in 18-month-old transgenic mice compared to an untreated transgenic group. Ubisol-Q10 treatment also activated autophagy in AD fibroblasts (presenilin-1 mutated) as well as in the brains of transgenic AD mice (Vegh et al. 2019). The authors found increased expression of autophagy-related genes beclin-1 and JNK1 following Ubisol-Q10 treatment. However, withdrawal of Ubisol-Q10 treatment led to the return of the former phenotype in AD fibroblasts indicating that constant supplementation of Ubisol-Q10 is required.

The mitochondria-targeting antioxidant MitoQ significantly increased neurite outgrowth and synaptic connectivity in neuron cell culture from a mouse model of AD, amyloid-β precursor protein transgenic mice (Manczak et al. 2010). MitoQ treatment also prevented amyloid-β-induced oxidative stress and all death of mouse cortical neuron cell culture from another model of AD, triple transgenic mice expressing three mutant human genes: amyloid-β precursor protein, presenilin-1 and four-repeat tau (McManus et al. 2011). The study focused on prevention of AD development described the improvement of cognitive decline, oxidative stress, β-amyloid accumulation, astrogliosis, synaptic loss and caspase activation in young triple transgenic mice given MitoQ in the drinking water at two months of age and continued for 5 months, i.e. the period during which the first AD-like pathologies become manifest (McManus et al. 2011). Young and Franklin (2019) focused on the therapy for AD. They evaluated the effects of MitoQ treatment on cognitive decline and neuropathologies in triple transgenic mice starting at 12 months after birth and continuing until 18 months of age, i.e. in the period during which all of the known AD-like pathologies are present and progressing. The authors found that MitoQ treatment of older AD mice was effective in improving memory retention compared to untreated mice. MitoQ-treated mice showed improved memory retention compared to untreated triple transgenic AD mice as well as reduced brain oxidative stress, synapse loss, astrogliosis, microglial cell proliferation, amyloid-β accumulation, caspase activation, and tau hyperphosphorylation. Additionally, MitoQ treatment inhibited synapse loss and significantly increased the abbreviated lifespan of the triple transgenic AD mice. These findings support the involvement of mitochondria-derived oxidative stress in the etiology of AD and suggest that MitoQ may lessen symptoms in AD patients.

**Amyotrophic lateral sclerosis**

Amyotrophic lateral sclerosis (ALS) is a devastating disease characterized by the death of motor neurons. The loss of motor neurons controlling voluntary muscles causes generalized progressive muscle weakness. Over time, patients lose the ability to walk, use their hands, speak, swallow, and breathe. Most ALS patients die within 3 to 5 years after diagnosis, usually as a result of respiratory failure. The ALS cause is mostly not known (about 10 % is familiar) and the effective therapy is still lacking. Mitochondrial alteration and oxidative stress are associated with ALS (Barber and Shaw 2010, Smith et al. 2019). Recently, Bond et al. (2018) and Wang et al. (2019) reported two systematic reviews on oxidative stress markers in ALS.

Molina et al. (2000) compared serum levels of CoQ10 and CoQ10/cholesterol ratio in 30 patients with ALS and 42 matched controls using a high-performance liquid chromatography. The mean serum CoQ10 levels and the CoQ10/cholesterol ratio did not differ significantly between the two studied groups. These values were not influenced by the clinical form (spinal vs. bulbar) of
ALS, and they did not correlate with age, age at onset, and duration of the disease. These results suggest that serum CoQ\textsubscript{10} concentrations are unrelated to the risk for ALS. However, Sohmiya \textit{et al.} (2005) observed a significant increase in oxidative form of CoQ\textsubscript{10} and in the ratio of oxidized form of CoQ\textsubscript{10} to total CoQ\textsubscript{10}. Moreover, percentage of CoQ\textsubscript{10} correlated significantly with the duration of illness suggesting systematic oxidative stress in the pathogenesis of the disease. Similarly, a significantly increased percentage of oxidized CoQ\textsubscript{10} in total plasma CoQ\textsubscript{10} in ALS patients was reported by Nagase \textit{et al.} (2016). Significantly higher plasma levels of thiobarbituric acid-reactive species (TBARS), marker of lipid peroxidation damage, but without changes in concentrations of plasma antioxidants (α-tocopherol, β-carotene, ubiquinol-10 and glutathione) in ALS patients compared to healthy controls were described by Oteiza \textit{et al.} (1997).

Matthews \textit{et al.} (1998) found that daily oral administration of 200 mg CoQ\textsubscript{10}/kg attenuated striatal lesions produced by systemic administration of 3-nitropropionic acid and slightly but significantly increased life span in a transgenic mouse model of familial ALS. On the other hand, the treatment of mouse model of familial ALS (SOD\textsubscript{1}\textsuperscript{G93A}) with oxidized (or reduced) CoQ\textsubscript{10} had no effect on disease progression (Lucchetti \textit{et al.} 2013). Experimental studies with targeted metabolic therapies supporting energy metabolism, which also contain CoQ\textsubscript{10}, improved motor function, quality of life and survival time of ALS patients (Ari \textit{et al.} 2014). A promising candidate for ALS treatment seems mitochondria-targeted antioxidant MitoQ, which has already been authorized for human medicine (Smith and Murphy 2010). Oral administration of MitoQ to SOD\textsubscript{1}\textsuperscript{G93A} mice starting at the onset of the symptoms extended their survival and improved grip strength (Mique\textit{el} \textit{et al.} 2014). MitoQ in SOD\textsubscript{1}\textsuperscript{G93A} mice also improved mitochondrial respiratory function in spinal cord and muscle, decreased nitrosative markers in central nervous system, decreased motor neuron loss and astrocyte reactivity in the spinal cord and maintained motor unit integrity.

In a clinical pilot trial, Ferrante \textit{et al.} (2005) assessed the safety and tolerability of high doses of CoQ\textsubscript{10} in ALS. They disclosed that doses as high as 3,000 mg CoQ\textsubscript{10}/day are safe and well tolerated in 31 ALS patients for as long as 8 months. However, the serum CoQ\textsubscript{10} level reached a plateau at a dose 2,400 mg/kg indicating that further studies need not exceed this high dose. Phase II trial of CoQ\textsubscript{10} for ALS (dose selection with 35 participants per group) compared two doses: high (2,700 mg/day) and moderately high (1,800 mg/day) in 9-month-period (Levy \textit{et al.} 2006, Kaufmann \textit{et al.} 2009). Unfortunately, the authors did not find any significant differences between selected dose 2,700 mg CoQ\textsubscript{10}/day and placebo subjects with 75 participants per group. Thus, the results did not provide sufficient evidence to justify a phase III trial for ALS treatment.

**Friedreich’s ataxia**

Friedreich’s ataxia (FA) is an autosomal recessive genetic and slowly progressive disease that causes difficulty in walking, a loss of sensation in the arms and legs and impaired speech. Moreover, life-threatening hypertrophic cardiomyopathy is the most severe manifestation. Reduced levels of the mitochondrial protein frataxin lead to cell-damaging oxidative stress (Bürk 2017). CoQ\textsubscript{10}, IDB and vitamin E were used as antioxidant treatment.

In an open-label study of 10 FA patients, antioxidant treatment (400 mg CoQ\textsubscript{10} plus 2,100 IU vitamin E per day) did not show any consistent benefits in the neurological evaluation after 6-month treatment (Lodi \textit{et al.} 2001). In all patient’s serum CoQ\textsubscript{10} level was increased and cardiac and skeletal muscle bioenergetics showed an improvement after 3-month-treatment (Lodi \textit{et al.} 2001). The 4-year-follow-up study with 77 patients confirmed an improvement in cardiac and skeletal muscle mitochondrial energy synthesis but only 7 patients showed some neurological improvement (Hart \textit{et al.} 2005). A high dose antioxidant therapy (600 mg CoQ\textsubscript{10} plus 2,100 IU vitamin E per day) provided no additional benefit when compared to a very low-dose antioxidant therapy (30 mg CoQ\textsubscript{10} plus 24 IU vitamin E per day) according to a two-year double-blind study with 50 FA patients (Cooper \textit{et al.} 2008). Serum CoQ\textsubscript{10} levels increased significantly in all patients. When compared cross-sectional data 49 % of all patients with CoQ\textsubscript{10} brought some evidence for stabilizing effects on the progression of some neurological parameters monitored by International Cooperative Ataxia Ratings Scale (ICARS).

The early studies with antioxidant and synthetic analogue of CoQ\textsubscript{10}, idebenone (IDB) used very low dose (5 mg/kg/day) and the numbers of participants were usually low (Artuch \textit{et al.} 2002, Buyse \textit{et al.} 2003, Mariotti \textit{et al.} 2003, Rustin \textit{et al.} 1999). The studies
showed various results in neurological aspects: from some improvement (Artuch et al. 2002, Di Prospero et al. 2007, Rustin et al. 1999) or no significant changes (Mariotti et al. 2003) till progressive worsening (Buyse et al. 2003). A retrospective analysis of 35 patients used IDB (5 mg/kg/day) for up to five years showed significantly deteriorated neurological parameters (Rinaldi et al. 2009). Brandsma et al. (2010) used intermediate dose of IDB (20 mg/kg/day) in 7 children’s patients. More than one-year therapy did not statistically change ICARS and Pediatric Quality of Life Inventory scores. Markedly higher doses of IDB were used in randomized, double-blind, placebo-controlled study (IONIA) with 70 ambulatory pediatric patients who were treated with low doses: 450 or 900 mg of IDB per day depending on body weight (≤ or > 45 kg) or high doses: 1,350-2,250 mg of IDB per day depending on body weight (≤ or > 45 kg) (Lynch et al. 2010). The study did not show any significant neurological improvement during the 6-month period. Sixty-eight patients followed by a 12-month-study (IONIA-E) were treated only with a high dose of IDB: 1,350-2,250 mg/day depending on body weight (≤ or > 45 kg). The authors concluded that this dose may offer a therapeutic benefit to pediatric FA patients by stabilizing the overall neurological function and improving fine motor skills and speech (Meier et al. 2012). Comprehensive reviews on the use of CoQ10 and IDB in FA were prepared by Spindler et al. (2009) and Parkinson et al. (2013).

Multiple sclerosis

Multiple sclerosis (MS) is a chronic, autoimmune, inflammatory and demyelinating neurodegenerative disease of central nervous system with a broad spectrum of motor, sensory and neuropsychiatric symptoms but the etiology is still unknown. Although there are currently drugs that can alleviate the symptoms of MS, the cure is not known. Mitochondrial dysfunction and abnormalities play their role in MS pathology (Campbell et al. 2012, Witte et al. 2013). Oxidative stress also accompanies this disease (Acar et al. 2012, Choi et al. 2018, Haider et al. 2011, Tasset et al. 2012).

Gironi et al. (2014) estimated significantly lower blood CoQ10 levels in MS patients in comparison with healthy subjects. On the other hand, de Bustos et al. (2000) did not find any significant differences between serum CoQ10 (and the CoQ10/cholesterol ratio) in a series of 31 patients with MS and 19 controls. Moreover, they did not find any correlation with age, age at onset or the duration of MS suggesting that the serum CoQ10 levels are an unrelated marker of risk or activity of MS. The possible explanation of the above difference can be that Gironi et al. (2014) had MS patients free of relapse or disease progression in the past 30 days, while de Bustos et al. (2000) studied patients during MS exacerbation. Therefore, the normal CoQ10 levels could be explained by an attempt of the organism to increase antioxidant mechanisms during an inflammatory phase of disease, which might thus compensate constitutive low CoQ10 levels (Gironi et al. 2014).

CoQ10 supplementation (500 mg/day for 12 weeks) decreased levels of the marker of oxidative damage, malondialdehyde and increased the activity of antioxidant enzyme superoxide dismutase. Nevertheless, total antioxidant capacity was decreased, and glutathione peroxidase activity was not affected in 48 patients with relapsing-remitting MS in a double-blind, placebo-controlled randomized clinical trial (Sanoobar et al. 2013). The same CoQ10 supplementation (500 mg/day for 12 weeks) lowered levels of two pro-inflammatory markers: serum tumor necrosis factor-α and interleukin-6 but did not change levels of anti-inflammatory markers: tumor necrosis factor-β and interleukin-4 in 48 patients with relapsing-remitting MS (Sanoobar et al. 2015). Participants reported reduced fatigue and depression compared to the placebo group (Sanoobar et al. 2016). However, further clinical trials with long-term observation and more participants are needed to elucidate the benefit of CoQ10 particularly in the immune-related inflammation processes (Zahednasab et al. 2015). Moccia et al. (2019) evaluated the wide set of laboratory markers of oxidative stress and inflammation in 60 relapsing-remitting patients with MS treated with 44 µg interferon-β1a and with 200 mg CoQ10. After 3-month-period, CoQ10 supplementation improved the scavenging activity, reduced the oxidative damage and induced shift towards a more anti-inflammatory milieu in peripheral blood of patients.

CoQ10 is also mentioned in some papers dealing with the nutritional parameters and suitable diets for MS patients (Armon-Omer et al. 2019, Bagur et al. 2017, Evans et al. 2018, Marx et al. 2020, Zuliani and Baroni 2015).

The most widely used animal model of MS is mouse experimental autoimmune encephalomyelitis (EAE). Mao et al. (2013) found that EAE (C57BL/6) mice with MitoQ pretreatment and treatment (i.p. 100
nmol/mouse (~30 g) twice per week for several weeks) reduced axonal loss and neurological disabilities associated with EAE. Moreover, a mitochondria-targeted antioxidant MitoQ significantly suppressed demyelination and inflammation of EAE, including the inhibition of inflammatory cytokines and chemokines. The authors confirmed neuroprotective and antioxidant roles of MitoQ by a co-culture of cortical neurons and microglia designed to mimic the mechanism of MS and EAE in vitro. Similarly, CoQ<sub>10</sub> administration (i.p. 10 mg/kg/three weeks) decreased significantly clinical symptoms and the level of the tumor necrosis factor α (TNF-α) versus interleukin 10 (IL-10) in EAE (C57BL/6) mice. Thus, CoQ<sub>10</sub> was capable to suppress the inflammatory pathway of MS (Soleimani et al. 2014).

Another experimental model for studying demyelination-remyelination uses a copper chelator, cuprizol (CPZ), which inhibits copper ions and causes oxidative stress, oligodendrocyte apoptosis and demyelination. CoQ<sub>10</sub> treatment of C57BL/6 mice alleviated oxidative stress induced by CPZ and dramatically suppress inflammatory biomarkers. (Khalilian et al. 2021).

**Noise-induced hearing loss**

Constant increased noise exposure is one of the most common causes of hearing loss. It is estimated that approximately 5% of the world population suffers from noise-induced hearing loss (NIHL) but its management and treatment are only poorly understood. Recent systematic review includes eleven articles with 701 patients and determines the effectiveness of current pharmacologic agents for the prevention of NIHL (Gupta et al. 2021). Various regimens included administration of several well-tolerated agents and known supplements such as α-lipoic acid, ambient oxygen, beta-carotene, carbugen, ebselen, Mg-aspartate, N-acetylcysteine, and vitamins C, E, and B<sub>12</sub>. Unfortunately, there is only limited number of heterogenous studies and future prospective, double-blinded, randomized, placebo-controlled clinical trials with standardized reporting of audiometric data are necessary to evaluate the clinical efficacy of pharmacological prevention for NIHL (Gupta et al. 2021).

Oxidative stress is one of the current theories of NIHL. Fetoni et al. (2013) followed the relationship between cochlear oxidative damage and repeated noise exposure in rat model of adult male Wistar rats. NIHL caused hearing loss, damage in hair cells and spiral ganglion. In addition, NIHL changed dendritic morphology and decreased spine number of pyramidal neurons of auditory cortices. Systemic administration of a hydrophilic CoQ<sub>10</sub> formulation (CoQ<sub>10</sub> terclaclate – Qter, i.p. 10 mg CoQ<sub>10</sub>/kg one hour before the acoustic trauma) reduced oxidative-induced cochlear damage, hearing loss and cortical dendritic injury.

**Hypertension**

Hypertension belongs to cardiovascular diseases but the brain plays an essential role in arterial blood pressure regulation. Rostral ventrolateral medulla (RVLM) is a brainstem site that generates sympathetic vasomotor tone and is an important center of blood pressure control (Guynet 2006, Hirooka et al. 2010, Sved et al. 2003). Animal models of neurogenic hypertension such as spontaneously hypertensive rats (SHR) have elevated the levels of superoxide anion and hydrogen peroxide in RVLM (Kimura et al. 2005, Kishi et al. 2004, Konno et al. 2012, Tai et al. 2005). Chan et al. (2009) recognized reduced mitochondrial electron capacity in RVLM of SHR. Local microinjection of CoQ<sub>10</sub> into RVLM of SHR restored a reduced mitochondrial electron transport chain capacity. Added CoQ<sub>10</sub> lessened the rotenone inhibition of respiratory chain complex I or antimycin A inhibition of respiratory chain complex III. Local application of CoQ<sub>10</sub> into RVLM of SHR promoted a dose-dependent decrease in mean arterial pressure and sympathetic vasomotor tone. On the other hand, there was only negligible effect of CoQ<sub>10</sub> treatment on superoxide level in RVLM of prehypertensive SHR or normotensive Wistar Kyoto rats (Chan et al. 2009).

The paraventricular nucleus (PVN) in the hypothalamus also plays an important role in the development of hypertension. PVN is an important central site for the coordination and regulation of autonomic response involving several excitatory and inhibitory neurotransmitters and pro- and anti-inflammatory cytokines. Adult male Sprague-Dawley rats fed a high-salt (8% NaCl) diet for 15 weeks developed hypertension with higher mean arterial pressure as compared to rats fed a normal salt (0.3% NaCl) diet (Gao et al. 2016). High-salt diet also increased levels of noradrenaline, tyrosine hydroxylase, interleukin-1β, NADPH oxidase 2 (NOX2) and NADPH oxidase 4 (NOX4) and lowered levels of gamma-aminobutyric acid (GABA), interleukin-10 and Cu/Zn superoxide dismutase (SOD) in PVN. The
concomitant CoQ_{10} treatment (10 mg/kg/day via oral gavage in rats fed a high-salt diet) for 15 weeks attenuated salt-induced hypertension. Moreover, CoQ_{10} supplementation restored the balance between excitatory and inhibitory neurotransmitters and the balance between pro- and anti-inflammatory cytokines in PVN. Thus, Gao et al. (2016) concluded that CoQ_{10} exerts its protective effects on hypertension just via restoring the appropriated balance in PVN.

Rats fed a high-fructose diet are the well-established rodent model for the study of human metabolic syndrome (Wu et al. 2014). The feeding of a high-fructose diet for 8 weeks caused an increase in sympathetic vasomotor tone and neurogenic hypertension in adult male Sprague-Dawley rats. RVLM of rats fed a high-fructose diet had increased level of reactive oxygen species due to depression of mitochondrial electron transport chain capacity and neuronal NO synthase (nNOS) uncoupling via upregulation of its protein inhibitor. Intracisternal infusion of CoQ_{10} attenuated sympathoexcitation and hypertension and significantly ameliorated all molecular events in rats fed high-fructose diet.

These three examples of hypertension show the variety of CoQ_{10} actions – the restoration of mitochondrial respiratory chain (Chan et al. 2009) or the correction of the balance in neurotransmitters and cytokines (Gao et al. 2016).

Hypertension affects approximately one billion subjects worldwide and is a major risk factor associated with cardiovascular events including coronary heart disease and cerebrovascular accidents. Some reviews summarized that CoQ_{10} administration can lower blood pressure without significant side effects in patients (Ho et al. 2016, Rosenfeldt et al. 2007).

Conclusions

From the first pioneering clinical administration of CoQ_{10} to patients with heart failure in Japan in the 60s of the last century the number of CoQ_{10} applications keeps increasing. In the context of mitochondrial dysfunction and oxidative stress in the above-mentioned serious neurological diseases the most prominent and relevant functions are the energetic role and antioxidant capacity of CoQ_{10}. New promising formulations improve bioavailability and could make possible the more efficient administration. Unfortunately, the listed neurological diseases need a more causative treatment. CoQ_{10} administration can serve only as a cooerorative substance. It is important to note that numerous clinical and experimental studies repetedly provide the evidence that CoQ_{10} is highly safe and good tolerated with negligible side effects or drug interactions.

Conflict of Interest

There is no conflict of interest.

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