Although it was first described in 1989, our understanding of coenzyme Q\textsubscript{10} (CoQ\textsubscript{10}) deficiency is only now coming of age with the recent first description of the underlying molecular defects. The diverse clinical presentations, classifiable into four major syndromes, raise the question as to whether the deficiencies are primary or secondary. Recent studies, including the one by Mollet, Rötig, and colleagues reported in this issue of the JCI, document molecular defects in three of the nine genes required for CoQ\textsubscript{10} biosynthesis, all of which are associated with early and severe clinical presentations (see the related article beginning on page 765). It is anticipated that defects in the other six genes will cause similar early-onset encephalomyopathies. Awareness of CoQ\textsubscript{10} deficiency is important because individuals with primary or secondary variants may benefit from oral CoQ\textsubscript{10} supplementation.

The first patients
In 1989 Ogasahara et al. described the first patients with coenzyme Q\textsubscript{10} (CoQ\textsubscript{10}) deficiency, presumably of the primary form (1). After normal early development, two sisters developed exercise intolerance and slowly developed progressive weakness of axial and proximal limb muscles. Around age five, brain involvement was manifested by learning disability in both sisters, seizures in one, and cerebellar syndrome in the other. In addition, both individuals had episodes of myoglobinuria following seizures or intercurrent infections. Family history suggested an autosomal recessive mode of inheritance. Laboratory abnormalities included lactic acidosis, increased serum creatine kinase levels, and myopathic electromyography.

Muscle biopsies showed the presence of ragged-red fibers (RRFs) and excessive accumulation of lipid droplets in type I fibers. The concentration of CoQ\textsubscript{10} was markedly decreased (about 5% of normal) in muscle from both patients but was normal in serum and cultured fibroblasts. It was concluded that the primary defect in this family probably involved a tissue-specific isozyme in the CoQ\textsubscript{10} synthetic pathway of muscle and brain. Although this study was published in a high-profile journal, the report was followed by a remarkably long silence: the next publications on patients with the same clinical triad (mitochondrial myopathy, recurrent myoglobinuria, and CNS signs) and muscle CoQ\textsubscript{10} deficiency appeared 8 and 11 years later (2, 3). Notably, all patients improved remarkably with oral CoQ\textsubscript{10} supplementation.

Infantile encephalomyopathy
In 2000, however, Rötig and coworkers reported a second and much more dramatic variant of CoQ\textsubscript{10} deficiency, which presented as an infantile mitochondrial encephalomyopathy with widespread CoQ\textsubscript{10} deficiency and, interestingly, nephrotic syndrome (not a common renal manifestation of respiratory chain defects) (4). This article was remarkable because it heralded the discovery of CoQ\textsubscript{10} biosynthetic defects, two of which were identified at the molecular level just a few months ago (5, 6). In the study by Mollet, Rötig, and colleagues in this issue of the JCI, additional gene defects have been identified and proven to have functional effects (7). In 2000, Rötig et al. (4) had reported three affected children in a sibship of four, who presented soon after birth with neurological symptoms, including nystagmus (an involuntary, rapid, rhythmic movement of the eyeball), optic atrophy, neurosensory hearing loss, ataxia, dystonia, and weakness. Nephrosis had been rapidly progressive in all three: one died of renal failure at eight years of age, and the other two required renal transplantation. Biochemical analyses in various tissues from those patients (as in samples from patients described by Mollet et al. in this issue; ref. 7) showed defects of respiratory chain reactions requiring CoQ\textsubscript{10}, and the defects were corrected in vitro by addition of a CoQ\textsubscript{10} analog to the reaction mixtures. Having found that CoQ\textsubscript{10} was undetectable in fibroblasts from one patient, Rötig et al. documented that CoQ\textsubscript{10} biosynthesis (measured in terms of [\textsuperscript{3}H]mevalonate incorporation into CoQ\textsubscript{10}) was, in fact, blocked. Suspecting a defect in decaprenyl diphosphate synthase, the authors sequenced prenyl-diphosphate synthase, subunit 1 (PDSS1), which encodes the human ortholog of the yeast COQ1 gene, in one patient but found no deleterious mutations.

Another remarkable feature of this disorder was the dramatic response of the two surviving patients to CoQ\textsubscript{10} supplementation.

The plot thickens
In the seven years separating Rötig’s 2000 paper (4) from the study in this issue (7) from the same group, the plot of the CoQ\textsubscript{10} deficiency story has considerably thickened. While studying the second patient with the “myopathy-plus” syndrome (2), we found that one of our disease control muscle samples, belonging to a young man with cerebellar ataxia, also had a very low concentration of CoQ\textsubscript{10}. This serendipitous observation led us to study more than 100 patients, mostly children, with genetically undefined autosomal recessive spinocerebellar ataxia. We identified 21 patients who had, besides cerebellar ataxia and cerebellar atrophy, various neurological symptoms, including seizures, developmental delay, mental retardation, or spasticity (8–10). Muscle biopsies showed neither abnormal mitochondrial proliferation nor lipid storage, but CoQ\textsubscript{10} levels were markedly decreased in both muscle and cultured fibroblasts. Similar patients have been reported by others (11–13). All patients responded, at least to some extent, to CoQ\textsubscript{10} supplementation.

The latest development in the CoQ\textsubscript{10} deficiency saga has been the identification of patients with isolated myopathy, usually slowly progressive and involving proximal limb and axial muscles: muscle biopsies characteristically show mito-
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CoQ₁₀ in mitochondrial metabolism. CoQ₁₀ is a vital component of the mitochondrial respiratory chain, where it shuttles electrons \( (e^-) \) to complex III from complexes I and II. CoQ₁₀ biosynthesis occurs mainly in mitochondria. Decaprenyl diphosphate is synthesized by a heterotetrameric enzyme composed of PDSSI and PDSS2 from mevalonate via farnesyl diphosphate and geranylgeranyl diphosphate and is attached to PHB by COQ2. Subsequently, at least 6 more COQ enzymes (COQ3–COQ8) catalyze methylation, decarboxylation, and hydroxylation reactions. A₈, ATP synthase subunit B; Cyt b, cytochrome b; FADH₂, flavin adenine dinucleotide, reduced form; ND1–6, subunits 1–6 of NADH dehydrogenase; PP, diphosphate; PDHC, pyruvate dehydrogenase complex.

Commentaries

Mitochondrial proliferation (as assessed by the observation of RRFs) and lipid storage (14, 15). Thus, it has become conventional to classify CoQ₁₀ deficiency into four major clinical categories: (a) myopathy with recurrent myoglobinuria and CNS involvement; (b) cerebellar ataxia with variable CNS involvement; (c) isolated myopathy; and (d) infantile mitochondrial encephalomyopathy. Because CoQ₁₀ in humans is almost completely synthesized endogenously, it has been assumed that these diverse syndromes are all due to primary CoQ₁₀ deficiency, and it has become commonplace to attribute the different clinical phenotype to blocks at different levels in the complex biosynthetic pathway of CoQ₁₀ (see Figure 1 in the article by Mollet et al.; ref. 7). In this pathway, decaprenyl diphosphate is synthesized from mevalonate via farnesyl diphosphate (which is also a precursor of cholesterol, steroids, and farnesylated proteins) and is attached to the para-hydroxybenzoate (PHB) ring by OH-benzoate polypropenyltransferase (COQ2). However, after this condensation reaction, at least six more
COQ10 deficiency: primary or secondary?

The central question in the burgeoning field of COQ10 deficiency is whether different clinical variants of the disease can all be ascribed to different biosynthetic errors or, alternatively, whether they encompass both primary and secondary forms of COQ10 deficiency. We now have experimental evidence that the second hypothesis is correct. Analysis of genome-wide microsatellite markers in a family with the ataxic variant of COQ10 deficiency suggested linkage of the disease to chromosome 9p13 and led to the identification in all three affected siblings of a homozygous mutation in the aprataxin (APTX) gene that causes ataxia oculomotor apraxia type 1 (AOA1) (17). Although the relationship between aprataxin, which is involved in nuclear DNA single-strand break repair, and COQ10 homeostasis remains to be clarified, this finding suggested that patients with the ataxic form of COQ10 deficiency should be examined for other gene defects causing autosomal recessive cerebellar ataxias (18). Metabolic defects in the mitochondrial respiratory chain or in other mitochondrial metabolic pathways may also result in COQ10 deficiency, although a study of 25 patients with mitochondrial encephalomyopathies, mostly due to mutations in mitochondrial DNA, showed a variable and, on average, mild (24%) decrease in muscle COQ10 level (19).

Defects of COQ10 biosynthesis

On the other hand, three recent articles, including the present one by Mollet et al. (5–7), have documented the existence of primary CoQ10 deficiency. Not too surprisingly, these biosynthetic defects have been associated with the earliest and most severe variant of CoQ10 deficiency, infantile mitochondrial encephalomyopathy. More surprising, and more difficult to explain, is the clinical heterogeneity that is already emerging even within this group of disorders. For example, the two siblings examined in the current study with mutations in the first subunit of COQ1, PDS1 (7), had a much milder phenotype (at the time of publication, they were 14 and 22 years of age, with obesity, hearing loss, optic atrophy, valvulopathy, and mild mental retardation) than the infant with mutations in PDS2, who was hypotonic at birth and died at 8 months of age after developing seizures, recurrent vomiting, cortical blindness, severe nephrosis, and the neuroradiological features of Leigh syndrome (6). Unfortunately, we have not been given any information on the neuroradiology of the siblings with mutations in PDS1: this would have been interesting, because in 2002 Van Maldergem et al. reported two sisters in their thirties with COQ10 deficiency and lifelong histories of encephalopathy, growth retardation, ataxia, deafness, mental retardation, lacrimal acidosis, and increased MRI signals in the caudate nucleus and putamen (20): they may also have had mutations in PDS1, and this might still be tested. In view of the rather striking response of these women to COQ10 supplementation, it is surprising that CoQ10 was not given by Mollet et al. to their patients, but perhaps this may still be attempted.

The patients with mutations in COQ2 had in common early-onset nephrosis and encephalopathy, but the infants homozygous for the Y297C mutation responded dramatically to COQ10 supplementation (5, 21), whereas those with the single-base-pair frameshift deletion at 1 and 12 days (7). On the other hand, there are striking clinical similarities between the family with the Y297C mutation in COQ2 (5) and that reported by Röting et al. in 2000 (4), including the severe nephrosis and the therapeutic effect of oral CoQ10 supplementation. It would be interesting to see whether the patients reported by Röting et al. also harbored mutations in COQ2.

COQ genes: six to go

In summary, primary and secondary CoQ10 deficiency have belatedly taken center stage in clinical research. Of the nine genes presumably involved in CoQ10 biosynthesis and suspected of causing primary CoQ10 deficiency, three — PDS1, PDS2, and COQ2 — have been found guilty. There is good reason to believe that mutations in the six genes still at large may soon be found to underlie human diseases. The paper by Mollet and Röting (7) should serve as a wake-up call for clinicians confronted with early-onset mitochondrial encephalomyopathies, especially if associated with glomerulonephrosis. The need for research is made more urgent by the fact that some of these patients may be helped and even saved by timely administration of high-dose CoQ10.

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