Clinical presentation and outcome in a series of 88 patients with the cblC defect.

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Compliance with Ethics Guidelines".

Informed Consent

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000.

Details of the contributions of individual authors

Planning and conduct of the study, evaluation of questionnaire returns, evaluation of data BF, MH, CD-V.

Design of questionnaire: BF, MB, CD-V.

Development of severity scores: MH.

Analysis of MRI data : FD

Handling of data and co-ordination of statistical analysis: SB

Manuscript preparation: BF, MH, MB, CD-V

Provision of patient material, validation of data and development of main conclusions:

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Summary

The cblC defect is the most common inborn error of vitamin B12 metabolism. Despite therapeutic measures, the long-term outcome is often unsatisfactory. This retrospective multicentre study evaluates clinical, biochemical and genetic findings in 88 cblC patients. The questionnaire designed for the study evaluates clinical and biochemical features at both initial presentation and during follow up. Also the development of severity scores allows investigation of individual disease load, statistical evaluation of parameters between the different age of presentation groups, as well as a search for correlations between clinical endpoints and potential modifying factors.

Results: No major differences were found between neonatal and early onset patients so that these groups were combined as an infantile-onset group representing 88% of all cases. Hypotonia, lethargy, feeding problems and developmental delay were predominant in this group, while late-onset patients frequently presented with psychiatric/behaviour problems and myelopathy. Plasma total homocysteine was higher and methionine lower in infantile-onset patients. Plasma methionine levels correlated with "overall impression" as judged by treating physicians. Physician's impression of patient's well-being correlated with assessed disease load.

We confirmed the association between homozygosity for the c.271dupA mutation and infantile-onset but not between homozygosity for c.394C>T and late-onset.

Patients were treated with parenteral hydroxocobalamin, betaine, folate/folinic acid and carnitine resulting in improvement of biochemical abnormalities, non-neurological signs and mortality. However the long-term neurological and ophthalmological outcome is not significantly influenced.

In summary the survey points to the need for prospective studies in a large cohort using agreed treatment modalities and monitoring criteria.

Key words: cblC defect; methionine; homocysteine; hydroxocobalamin; betaine; methylmalonic aciduria; homocystinuria.

Introduction

The cblC defect is the most common inborn error of vitamin B12 (cobalamin, Cbl) metabolism and is caused by mutations of the *MMACHC* gene as described in over three hundred patients (Lerner-Ellis *et al.*, 2006, Nogueira *et al,.*2008, Lerner-Ellis *et al.,*2009).

Cobalamin must be obtained from animal dietary products such as milk and meat (Fowler *et al*., 1998). Absorption of Cbl requires binding to specific proteins in saliva, proteolytic release and binding to intrinsic factor in the intestine and uptake into the enterocyte via a specific receptor. After release from its complex with intrinsic factor, Cbl enters the circulation bound to transcobalamin and is taken up into lysosomes through endocytosis. After release into the cytosol Cbl is converted to its two active co-enzymes, methylcobalamin in the cytosol and adenosylcobalamin in the mitochondrion. Adenosylcobalamin is the co-enzyme for methylmalonyl-CoA mutase, deficiency of which results in methylmalonic aciduria, one of the biomarkers of the cblC defect. Methylcobalamin is a co-factor for N5-methyltetrahydrofolate: homocysteine methyltransferase, deficiency of which results in an increase of homocysteine with low levels of methionine, other biochemical hallmarks of the cblC defect (Fowler *et al.*, 1998).

Clinical presentation and severity of the cblC defect can vary considerably ranging from severe burden of disease and even death at an early age to late presenting disabilities (Bodamer *et al.*, 2001). In particular, patients with early onset of symptoms (<1 year of life) were reported to show an unfavourable outcome with average survival of less than 10 months and mortality exceeding 25%, whereas patients with late onset (defined by the authors as >4 years of life) survived with a better prognosis following treatment (Rosenblatt *et al.*, 1997).

So far, only one study reports the frequency of symptoms within a large series of 50 cblC patients (Rosenblatt *et al.*, 1997) and several smaller studies and individual case reports have focused on particular features (Table 1). In late onset or adult cases, clinical features include predominantly neurological disturbances, dementia, myelopathy, and thromboembolic complications (Shinnar *et al.*, 1984; Thauvin-Robinet *et al.*, 2008). A limitation of many of these studies and case reports is the lack of a clear indication of whether or not symptoms were initially present at diagnosis or if they developed during the subsequent course of the disease while patients were treated.

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Treatment with intramuscular hydroxy-Cbl (OH-Cbl), betaine and carnitine is reported to improve biochemical abnormalities including restoration of plasma methionine values to normal (Ribes *et al.*, 1990; Bellini *et al.*, 1992; Bartholomew *et al.*, 1998; Anderson *et al.*, 1999). Plasma homocyst(e)ine levels or methionine levels were not improved by the cyano form of Cbl (Andersson *et al.*, 1998) given intramuscularly and/or folinic acid (Bartholomew *et al.*, 1998). The long term outcome of the cblC defect remains poor in most cases, even when these therapeutic measures were introduced soon after initial presentation and in some cases even prenatally (Huemer *et al.*, 2005). Further, there is no consensus on the optimal treatment for this severely debilitating disorder (Martinelli *et al.*, 2011b).

This questionnaire based study evaluates clinical findings at initial presentation and during the disease course whilst treated in 88 cblC deficient patients with the following aims: i) to evaluate patients according to age of presentation and to assess possible prognostic indicators; ii) to document the natural history of the cblC defect over time with particular reference to clinical signs both at diagnosis and during the course of the disease; iii) to investigate genotype-phenotype correlations; and iv) to evaluate therapeutic measures.

Patients and methods

Study population and recruitment of patients

The study was approved by the ethics committee of the University of Basel (Ref.Nr.EK:267/04). A total of 88 patients were included in the study. Patients were recruited in three ways. First those from whom cell lines were sent to the University Children's Hospital, Basel for confirmation of diagnosis between January 1987 and May 2005; second, additional patients reported at a workshop held at the 36th EMG Meeting in Rimini 2004; third, further confirmed cases of the cblC defect known to the contacted physicians. Diagnosis was based on the finding of increased homocysteine, either free or total, and methylmalonic acid in plasma and/or urine shown not to be due to nutritional vitamin B12 deficiency. In 75 cases the diagnosis was confirmed by studies of methionine and serine synthesis, propionate incorporation into cell proteins and Cbl uptake and coenzyme synthesis and somatic complementation analysis in fibroblasts performed at the

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University Children's Hospital Basel (Fowler and Jacobs, 1998). Following discovery of the gene for cblC the molecular defect was confirmed by mutation analysis.

Questionnaire based survey

A questionnaire was sent to 49 international metabolic centres with full returns received from 26 centres. The questionnaire items were developed on the basis of a specialist meeting and a review of the literature on cblC. Items covering clinical presentations and features as reported in the literature and open questions on yet unreported organ involvement at diagnosis and during the course were selected. In addition, information was requested on personal data, family history, pregnancy and birth complications, age at first symptoms and at diagnosis, biochemical parameters at diagnosis and during the course, and treatment modalities.

The presence or absence of each specific symptom both at the time of diagnosis and during the course of the disease was recorded. Prenatal symptoms were recorded and different symptoms were grouped according to affected organ systems (supplementary table 1)

We developed a severity score in order to estimate the disease load in the individual both at presentation and during the course. Thus nutritional symptoms, general development, neurological symptoms, eye problems, renal, cardiac and haematological involvement as well as abnormalities in brain MRI scans were numerically assessed and summed to give a ***severity score*** ranging from 0 (no symptoms) to 25 (all symptoms present). In addition the physician's ***overall impression*** on the disease outcome and the present state in each patient was determined by scoring mental status, visual impairment, motor development and quality of life. Zero, one and two points were allocated for normal, moderately impaired and severely impaired, respectively. Deceased patients were allocated a score of 2 points for each category to give a total possible score of 8 (see supplementary table 1). Questionnaires were completed by the physicians caring for the patient and returned to the University Children's Hospital Basel. Following evaluation of initial returns the submitted information was incorporated into the database and returned to the responsible physician for checking and to reply to additional questions.

In those cases where only free homocysteine disulphide values were available, an estimate of the total plasma homocysteine was made. This was based on the observation in 2 studies (Moat *et al.*, 1999; B. Fowler, unpublished data) which showed that free homocystine is only found in samples in which total

homocysteine exceeds 70µmol/l. Therefore an estimate of total homocysteine was calculated by adding 70 to double the free homocystine concentration. This approach seems to be justified by the observation that there was no significant difference of mean values and standard deviation between the groups of only measured total homocysteine versus measured plus estimated values (2 tailed t-test).

Statistical analysis

Both severity score and physician's overall impression were compared with various other parameters by statistical analysis. The various statistical methods used for comparisons of data are indicated in the results. For all statistical analysis significance was assigned to p values below 0.05.

Results

Age distribution and demographic data

The age of presentation in all patients ranged from 0-162 months with a median value of 0.91 months. As shown in Figure 1, 43 patients presented below one month (neonatal onset), 33 between 1 month and 1 year of age (early onset) and 10 above 1 year of age (late onset). Two patients were detected by neonatal family screening. There was evidence of consanguinity in a total of 26 patients.

The ethnic origin was reported as European in 54 unspecified Caucasian in 17, Asian in 4 with no information in 13. Among the European patients 27 were from Southern countries including Italy, Portugal and Spain. The male to female distribution of 58 to 30 (ratio 1.93) was uneven. A total of 10 subjects had died. (supplementary figure 1) Seven (6 male, 1 female) patients died before 3 months of age, 3 female patients died at 20 months, 4 years and 16 years respectively. In surviving patients, age at final evaluation ranged from 9 months to 47 years and 7 months (mean 123.4 months; S.D. 93.5, median 88.5 months).

Clinical symptoms at onset and during disease course according to subgroups

Figure 2 summarises clinical signs showing the overall frequency of the different findings both at initial clinical presentation and at the last evaluation during the course of the disease. Symptoms such as personality changes and mental retardation were only evaluated after the third month of age.

Comparison of the clinical, biochemical and molecular features between the age groups

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Initially all quantitative parameters and individual clinical severity scores listed in supplementary table 2 were compared for patients with neonatal, early and late onset according to the classification suggested by Rosenblatt et al. (1997). Statistical analysis was performed using the Mann-Whitney U test for non-parametric variables. Evaluation of data in the neonatal onset and early onset group revealed few statistically significant differences. These were the higher prevalence of microcephaly in the early onset patients both at diagnosis (p = 0.0085) and during the course (p = 0.049), and a higher severity score for general development at diagnosis in early-onset compared with neonatal-onset patients (p = 0.02). Due to the close clinical similarity and overall lack of statistical differences between neonatal and early onset patients, these two groups were combined and termed as "infantile onset" for further comparisons with late onset patients.

Infantile onset patients showed significantly higher scores for nutritional signs and microcephaly (all p≤0.015) both at diagnosis and during the disease course, when compared with late onset patients. At follow-up alone, significant differences were found between the two groups for total severity score, general development, overall impression and eye-related problems (all p ≤0.026). Considering the biochemical parameters, the infantile onset group showed lower methionine levels at diagnosis (median 8.0 *vs.* 14.0 µmol/l; p=0.017) and higher homocysteine values at follow-up (55.5 *vs.* 35.0 µmol/l; p=0.013).

Statistical correlations were analysed using the Spearman Rank test between various parameters and the severity score at diagnosis; the severity score during the course and the overall impression for all patients together and for the different age groups. This test showed a number of correlations. First, age at diagnosis and delay in diagnosis correlates with severity score at diagnosis (p <0.002). Second, total severity score at diagnosis correlates with both severity score and overall impression at follow up (p<0.0001). Third, microcephaly and eye-related signs at diagnosis and during the course correlate with severity score at follow-up (p<0.001). In the late onset patients plasma homocysteine and urine MMA levels correlate with the severity score and with overall impression (p<0.05), whereas in infantile onset patients plasma homocysteine alone at diagnosis correlates with the severity score during the course. Regardless of the age at presentation, plasma methionine negatively correlates with overall impression at follow-up (p = 0.048).

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Plasma homocysteine levels during the course showed a positive correlation with all clinical parameters in late onset patients.

Brain MRI

Brain MRI findings were available from 64 patients (49 infantile and 7 late onset cases). Normal findings were present in only 19% of patients. Brain atrophy and white matter abnormality were seen in both infantile (14/49 and 16/49 respectively) and late onset (4/7 and 1/7 respectively) cases. The most striking differences between the age groups were the finding of hydrocephalus (15/49 patients) and of basal ganglia lesions (6/49 patients) only in infantile onset cases.

Treatment modalities and correlations with clinical outcome

Different treatment modalities were used. Sixty-nine of 76 infantile and 9 of 12 late onset patients were treated with parenteral OH-Cbl. Patients not given OH-Cbl were mainly ones who died from the disease. Betaine (oral dose ranged from 200 – 10.000 µg/kg/d) was used in 67 infantile and 6 late onset patients, folate or folinic acid were applied in 57 infantile and 4 late onset cases (oral dose ranged from 14-10.000 µg/kg/d. Carnitine was given to 37 infantile and 2 late onset patients. Supplemental methionine was used only in one patient. No patients were treated with protein restricted diet.

Contingency tables showed no correlation between the use of carnitine, betaine or folate and the total severity score during the course of the disease (two sided Exact Fisher test). Furthermore, the Spearman rank test revealed no correlation between the dose of betaine and either median methionine levels or total homocysteine levels during the course of the disease.

Genetic analyses

Molecular genetic analysis of *MMACHC* was performed by either the group of D.S. Rosenblatt or B. Fowler (personal communication) in 74 patients (supplementary Table 3). The most common mutations identified were the c.271dupA and c.394C>T mutations. Of a total of 148 mutant alleles 73 were c.271dupA (49%) and 30 were c.394C>T (20%). Homozygosity for the c.271dupA mutation was present in 23 patients (22 with infantile onset) and the c.394C>T mutation in 10 patients (6 with infantile onset). Two infantile onset patients were homozygous for c.331C>T and a further two were homozygous for c.217C>T. In addition, 15 private mutations were identified.

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Discussion

This questionnaire based retrospective survey addresses a comprehensive range of features in the largest number of patients with the cblC defect so far studied, extending the report on 50 patients by Rosenblatt *et al.* (1997). We are aware of a selection bias in the recruitment of either patients from whom cell lines were sent for confirmation of diagnosis to a single metabolic laboratory or patients who were known to the involved metabolic specialists. Nevertheless until now, as in most inborn of errors of metabolism no registry or any other unbiased patient reporting system has been implemented for cblC patients. Study patients stemmed mainly from Europe with only 4 non-Caucasian and a predominance of cases from southern Europe reflecting our catchment area rather than the world-wide ethnicity reported in whom mutation analysis was undertaken (Lerner-Ellis *et al.*, 2009).

The degree of consanguinity was high being reported in 26 cases.

Regarding gender of the patients there was a clear imbalance towards males, with a male to female ratio close to 2, which constitutes new information. Whether this is because of lack of detection or increased intra-uterine mortality for females can only be speculated on. Ten patients (9 with infantile onset) died in total, representing 11.4% of cases compared with 26% of patients in the previous cohort (Rosenblatt *et al.* 1997) possibly reflecting earlier diagnosis and different or improved treatment modalities.

In contrast to the study by Rosenblatt *et al.* (1997) we differentiate between clinical and biochemical features present at diagnosis and those at follow up. This allows a better understanding of the natural history of the disease and of the response to treatment. Evaluation of variables in the different presenting age groups was backed up by statistical analysis allowing a search for significant correlations between clinical end points and possible modifying factors.

In addition to assessment of individual features we also created organ specific and overall severity scores to obtain a quantitative index for comparison with possible modifying factors. We are aware of the shortcomings of the approach of using overall, non standardized scores but it has been shown in other multi-systemic diseases that severity or disease activity scores are extremely helpful in clinical practice and

evaluation of treatment and may add to the information deduced from laboratory parameters. Nevertheless the weighting of symptoms and organ damage and the proof of validity and reliability of severity scores is a challenging task which may only be achieved over years and by analysis of larger cohorts (Gladman et al. 2002). Therefore the severity score developed for our study constitutes a first attempt to establish the general idea of assessment of patients' symptoms in a more systematic manner. Physician's overall assessment of disease severity is an established parameter for assessing disease severity in other multi-systemic diseases (Gutierrez-Suarez 2007; Seid et al 2013) but has until now only rarely been used in the field of metabolic diseases.

The previous survey by Rosenblatt *et al.*(1997) reported patients below one year of age as early onset (44 patients) and above 4 years of age as late onset (6 patients). As stated in the results section we combined the neonatal and early onset patients as infantile onset. Thus the infantile onset group contained 88% of patients, half presenting by one month of age and 38% between 1 month and 1 year of age. The remaining12% of patients presented after the chosen cut off of one year of age and were assigned to the late presentation group. The overall median age of presentation observed in our series is close to the one month reported in the previous cohort.

The study of the natural course of the CblC defect underlines that the cblC defect needs to be considered in the differential diagnosis of a wide range of conditions. **At initial presentation** there are several rather non-specific symptoms occurring in more than half of patients such as hypotonia/weakness, lethargy, feeding difficulties and developmental delay. More specific signs, related to diffuse microangiopathic damage (Martinelli *et al.*, 2011), include hydrocephalus, detected in about one third of infantile onset patients, and haemolytic uraemic syndrome. Other symptoms were eye-related signs and cardiomyopathy, present in less than 10% of patients, psychiatric disorders, spasticity and myelopathy. Since these complications are severe and have only been reported anecdotally in this disorder, our study confirms their importance.

Clinical features were significantly different between the infantile and late onset patients. Hypotonia/weakness, lethargy, feeding difficulties, failure to thrive, nystagmus, dysmorphic features and optic atrophy at diagnosis were all clearly more prominent in infantile onset patients. Developmental delay

and seizures were of similar incidence. In late onset patients, psychiatric changes (personality changes, confusion/disorientation) and spasticity were fairly common features. Myelopathy was almost exclusive to the late onset patients. Apart from the differences in the selection parameters there was a statistically significant better general condition at presentation and lack of microcephaly and cardiomyopathy in late onset patients.

Evaluation of findings **during the course of the disease,** following treatment reveals that the non-neurological signs resolve after treatment. Thus anaemia, acidosis and macrocytosis all disappeared after treatment. Also hypotonia/weakness, lethargy, feeding difficulties, hydrocephalus, HUS and cardiomyopathy became less frequent. Since some of these complications are potentially fatal (e.g. HUS), treatment not only improves some clinical outcomes but reduces mortality.

In contrast, neurological and ophthalmological problems such as developmental delay, seizures, failure to thrive, microcephaly, dysmorphic features, spasticity and optic atrophy remained at about the same frequency. Also there was an increase of prevalence of nystagmus, strabismus, pigmentary retinopathy, visual impairment despite treatment in infantile onset patients. Therefore the treatment modalities currently employed here appear not to have completely altered the disease course, confirming previous assumptions of a poor long-term neurological prognosis regardless of treatment and biochemical amelioration (Martinelli *et al.*,2011, Weisfeld-Adams et al 2013). On-going decline in IQ over time has been reported by Beauchamp *et al* (2009) in two patients despite therapy.

We found no correlation between the dose of either OH-Cbl or betaine administered and score parameters during the disease course. A wide variety of treatment modalities have been applied especially concerning the dose and interval of medication (e.g.OH-Cbl, betaine), pointing to the need to understand whether optimization of known and/or the development of new treatment strategies might positively change the disease course (Dionisi-Vici *et al.*, 2013). A recent retrospective literature review reporting on both early and late onset patients suggested that daily treatment with parenteral OH-Cbl combined with betaine results in a better outcome (Carillo-Carrasco et al 2012a,b).

In this regard only one patient in our survey was treated with supplemental methionine, which has been claimed to be successful in individual cases of other disorders of defective remethylation (Kvittingen *et al.*,

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1997; Abeling *et al*., 1999).The recent observation both *in vitro* and *in vivo* of increased oxidative stress and of abnormal glutathione status in cblC defect (Jorge-Finnigan *et al.*, 2010; Pastore *et al.*, 2013; Richard *et al.*, 2009), may suggests the use of antioxidant therapy to correct redox state abnormalities and its potentially related clinical signs.

Of the biochemical features, plasma methionine was higher at diagnosis and plasma homocysteine was lower during the disease course in late onset patients. The finding that only plasma methionine levels were correlated with overall impression is supported by the correlation of methionine levels and assessment of adaptive behaviour skills by parents / caregivers (Weisfeld-Adams et al 2013), suggesting a potential contribution of reduced methionine availability in the pathogenesis of some of the clinical signs of the disease (Martinelli *et al.*, 2011). Nevertheless, severity scores showed no significant correlation with methionine.

The only correlation observed with factors affected by treatment, was the aforementioned relationship of total homocysteine measured during the course of the disease and overall impression.

Regarding possible genotype-phenotype correlations, results of mutation analysis showed that the homozygosity for the c.271dupA mutation correlates with infantile presentation. These findings support the previous suggested idea that c.271dupA is associated with infantile onset. Homozygosity for the c.394C>T mutation was seen in six infantile presenting patients and in 4 late presenting patients This apparent contradiction with the previously reported correlation between late onset and this mutation (Morel *et al*., 2006; Nogueira *et al.*, 2008) may be related to differences in the classification of patients.

Recently, the cblC defect has been included in some countries in the panel of diseases screened for by expanded newborn screening (Carrillo-Carrasco *et al.*, 2012a). However, neither the management nor the outcome of asymptomatic patients with cblC detected by newborn screening has been extensively studied. At present there is only anecdotal data suggesting that earlier diagnosis of affected subjects through expanded newborn screening improves overall outcome but not neurological and ocular symptoms (Weisfeld-Adams 2013; C. Dionisi-Vici personal observation). The report of a family showing a non-neurological phenotype with fatal isolated pulmonary hypertension at the age of two years in one sibling and with haemolytic uremic syndrome at the age of three years in the eldest one (Iodice *et al.*, 2013),

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highlights the possibility that if expanded newborn screening would have been performed, these two brothers might have experienced a different clinical outcome. Early intervention preceding the appearance of severe signs related to micro-angiopathy might well be expected to also avoid the occurrence of hydrocephalus, one of the more severe abnormalities occurring in the cblC defect.

Taken together, these findings confirm that an exact comprehensive understanding of the pathophysiology of cblC defect has still not been achieved. Lack of good developmental and neurological outcome may reflect possible irreversibility of pathogenetic mechanisms in this multifactorial defect. Additionally, it is likely that the synergistic effect of different mechanisms, which include the accumulation of putatively toxic metabolites and the deficiency of products downstream of the enzymatic defect(s), is responsible for the multisystem organ involvement (Martinelli *et al*., 2011).

In summary, this survey points to the need for careful prospective multi-centre studies as recently started with the European Network and Registry for Homocystinurias and Methylation Defects (E-HOD) using agreed treatment modalities and monitoring parameters since present treatment regimes do not fully improve the disease course.

Acknowledgments

References

Abeling NGGM, van Genip AH, Blom H, et al. Rapid diagnosis and methionine administration: Basis for a favourable outcome in a patient with methylene-tetrahydrofolate reductase deficiency. J Inherit Metab Dis 1999; 22: 240-2.

Andersson HC, Merble M, Shapira E. Long-term outcome in treated combined methylmalonic aciduria and homocystinuria. Genet Med 1999; 1:146-50.

Andersson HC, Shapira. Biochemical and clinical response to hydroxocobalamin versus cyanocobalamin treatment in patients with combined methylmalonic aciduria and homocystinuria (*cblC*). J Pediatr 1998; 132: 121-4.

Bartholomew DW, Batshaw ML, Allen RH, et al. Therapeutic approaches to cobalamin C methylmalonic acidemia and homocystinuria. J Pediatr 1998; 112: 32-9.

Beauchamp MH, Anderson V, Boneh A.Cognitive and socialn profiles in two patients with cobalamin C disease.J Inherit Metab Dis. 2009 Dec;32Suppl 1:S327-34. doi: 10.1007/s10545-009-1284-8. Epub 2009 Oct 15.

Bellini C, Cerone R, Bonacci W, et al. Biochemical diagnosis and outcome of 2 years treatment in a patient with combined methylmalonic aciduria and homocystinuria.Eur J Pediatr 1992; 151: 818-20.

Biancheri R, Cerone R, Schiaffino MC, et al. Cobalamin (Cbl) C/D deficiency: clinical, neurophysiological and neuroradiologic findings in 14 cases.Neuropediatrics. 2001; 32: 14-22.

Biancheri R, Cerone R, Rossi A, et al. Early-onset cobalamin C/D deficiency: epilepsy and electroenchephalographic features. Epilepsia 2002; 43: 616-22.

Bodamer OA, Rosenblatt DS, Appel SH, Beaudet AL. Adult-onset combined methylmalonic aciduria and homocystinuria (cblC). Neurology 2001; 56: 1113.

Bodamer O, Fowler B Workshop CobalaminC/D In Proceedings of 36th EMG Meeting Rimini May 14-16 2004. Milupa Publications.

Brandstetter Y, Weinhouse E, Splaingard ML, Tang TT. Corpulmonale as a complication of methylmalonic acidemia and homocystinuria (Cbl-C type).Am J Med Genet 1990; 26:167-71.

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Carrillo-Carrasco N, Chandler RJ, Venditti CP. Combined methylmalonic academia and homocystinuria, cblC type. I. Clinical presentations, diagnosis and management. J Inherit Metab Dis 2012a;35:91-102

Carrillo-Carrasco N, Venditti CP. Combined methylmalonic academia and homocystinuria, cblC type. II. Complications, pathophysiology and outcomes. J Inherit Metab Dis 2012b;35:103-14

Cerone R, Schiaffino MC, Caruso U, Lupino S, Gatti R. Minor facial anomalies in combined methylmalonic aciduria and homocystinuria due to a defect in cobalamin metabolism. J Inherit Metab Dis 1999; 22: 247-50.

Dionisi-Vici C, Martinelli D, Ceravolo F, Boenzi S, Pastore A. Optimizing the dose of hydroxocobalamin in cobalamin C (cblC) defect. Mol Genet Metab 2013;doi: S1096-7192(13)00179-0

Ellaway C, Christodoulou J, Kamath R, Carpenter K, Wilcken B. The association of protein-losing enteropathy with cobalamin C defect. J Inherit Metab Dis 1998; 21: 17-22

Fowler B, Jakobs C. Post- and Prenatal diagnostic methods for the homocystinurias.Eur J Pediat 1998; 157:88-93.

Fowler B. Genetic defects in folate and cobalamin metabolism. Eur J Pediatr. 1998; 157 Suppl: S60-6.

Gladman DD, Ibañez D, Urowitz MB., Systemic lupus erythematosus disease activity index 2000. J Rheumatol. 2002;29:288-91.

Geraghty MT, Perlman EJ, Martin LS, et al. Cobalamin C defect associated with hemolytic –uremic syndrome. J Pediatr 1992; 120: 934-7.

Grünert SC, Fowler B, Superti-Furga A, Sass JO, Schwab KO. Hyperpyrexia resulting in encephalopathy in a 14-month-oldpatient with cblC disease.Brain & Develop 2011; 33:432-6.

Gutiérrez-Suárez R, Pistorio A, Cespedes Cruz A, Norambuena X, Flato B, Rumba I, Harjacek M, Nielsen S, Susic G, Mihaylova D, Huemer C, Melo-Gomes J, Andersson-Gare B, Balogh Z, De Cunto C, Vesely R, Pagava K, Romicka AM, Burgos-Vargas R, Martini A, Ruperto N; Pediatric Rheumatology International Trials Organisation (PRINTO). Health-related quality of life of patients with juvenile

idiopathic arthritis coming from 3 different geographic areas. The PRINTO multinational quality of life cohort study. Rheumatology 2007 ;46:314-20

Heil SG, Hogeveen M, Kluijtmans LA, et al. Marfanoid features in a child with combined methylmalonic aciduria andhomocystinuria (CblC type). J Inherit Metab Dis 2007;30:811.

Heinemann MK, Tomaske M, Trefz FK, Bosk A, Baden W, Ziemer G. Ventricular septal defect closure in a neonate with combined methylmalonic aciduria/homocystinuria. Ann Thorac Surg. 2001; 72:1391-2.

Huemer M, Simma B, Fowler B, Suormala T, Bodamer OA, Sass JO. Prenatal and postnatal treatment in cobalamin C defect. J Pediatr 2005; 147: 469-72.

Iodice FG, Di Chiara L, Boenzi S, et al. Cobalamin C defect presenting with isolated pulmonary hypertension. Pediatrics 2013; 132:e248-51

Jorge-Finnigan A, Gámez A, Pérez B, Ugarte M, Richard E. Different altered pattern expression of genes related to apoptosis in isolated methylmalonic aciduriacblB type and combined with homocystinuria cblC type. BiochimBiophysActa. 2010; 1802: 959-67

Kvittingen EA, Spangen, S, Lindemans J, Fowler B. Methionine synthase deficiency without megaloblastic anaemia. Eur J Pediat 1997; 156: 925-30.

Lerner-Ellis JP, Tirone JC, Pawelek PD, et al. Identification of the gene responsible for methylmalonic aciduria and homocystinuria, cblC type. Nat Genet 2006; 38: 93–100.

Lerner-Ellis JP, Anastasio N, Liu J, et al. Spectrum of mutations in MMACHC, allelic expression, and evidence for genotype-phenotype correlations.Hum Mutat 2009;30:1072-81.

Longo D, Fariello G, Dionisi-Vici C, et al. MRI and 1H-MRS findings in early-onset cobalamin C/D defect. Neuropediatrics 2005; 36: 366-72.

Mamlock RJ, Isenberg JN, Rassin DN. A cobalamin metabolic defect with homocystinuria, methylmalonic aciduria and macrocytic anaemia. Neuropediatrics 1986; 17: 94-9.

Martinelli D, Dotta A, Massella L, et al. Cobalamin C defect presenting as severe neonatal hyperammonemia. Eur J Pediatr 2011a; 170: 887-90

Martinelli D, Deodato F, Dionisi-Vici C. Cobalamin C defect: natural history, pathophysiology, and treatment. J Inherit Metab Dis 2011b; 34: 127–35.

Mitchell BA, Watkins D, Melancon SB, et al. Clinical heterogeneity in cobalamin C variant of combined homocystinuria and methylmalonic aciduria. J Pediatr 1986; 108: 410-5.

Moat SJ, Bonham JR, Tanner MS, Allen JC, Powers HJ. Recommended approaches for the laboratory measurement of homocysteine in the diagnosis and monitoring of patients with hyperhomocysteinaemia. Ann Clin Biochem 1999; 36: 372-9.

Morel CF, Lerner-Ellis JP, Rosenblatt DS. Combined methylmalonicaciduria and homocystinuria (Cbl-C): phenotypegenotypecorrelations and ethnic-specific observations. Mol Genet Metab 2006; 88: 315–21.

Nogueira C, Aiello C, Cerone R,et al. Spectrum of MMACHC mutations in Italian and Portuguese patients with combined methylmalonic aciduria and homocystinuria, Cbl-C type. Mol Genet Metab 2008; 93: 475–80

Pastore A, Martinelli D, Piemonte F, et al. Glutathione metabolism in cobalamin deficiency type C (cblC). J Inherit Metat Dis 2013 *in press*

Patton N, Beatty S, Lloyd IC, Wraith JE. Optic atrophy in association with cobalamin C (cblC) disease. Ophthalmic Genet 2000; 21: 151-4.

Profitlich LE, Kirmse B, Wasserstein MP, Diaz GA, Srivastava S. High prevalence of structural heart disease in children with Cbl-C-type methylmalonic aciduria and homocystinuria. Mol GenetMetab 2009; 98: 344–8.

Ribes A, Briones P, Vilaseca MA, et al. Methylmalonic aciduria with homocystinuria: Biochemical studies, treatment, and clinical course of a Cbl-C patient. Eur J Pediatr 1990; 149: 412-5.

Ricci D, Pane M, Deodato F, et al. Assessment of visual function in children with methylmalonic aciduria and homocystinuria.Neuropediatrics 2005; 36: 181-5.

Richard E, Jorge-Finnigan A, Garcia-Villoria J, et al. Genetic and cellular studies of oxidative stress in methylmalonic aciduria (MMA) cobalamin deficiency type C (cblC) with homocystinuria (MMACHC). Hum Mutat 2009; 30:1558-66

19

Robb RM, Dowton SB, Fulton AB, Levy HL. Retinal degeneration in Vitamin B 12 disorder associated with methylmalonic aciduria and sulfur amino acid abnormaltities. Am J Ophthalmol 1984; 97: 691-6.

Rosenblatt DS, Aspler AL, Shevell MI, Pletcher BA, Fenton WA, Seashore MR. Clinical heterogeneity and prognosis in combined methylmalonic aciduria and homocystinuria (CblC). J Inherit Metab Dis 1997; 20: 528-38.

Roze E, Gervais D, Demeret S, et al. Neuropsychiatric disturbances in presumed late onset cobalamin C disease. Arch Neurol. 2004; 60: 1457-62.

Seid M, Huang B, Niehaus S, Brunner HI, Lovell DJDeterminants of health-related quality of life in children newly diagnosed with Juvenile Idiopathic Arthritis. Arthritis Care Res. 2013 Aug 27. doi: 10.1002/acr.22117. [Epub ahead of print]

Sharma AP, Greenberg CR, Prasad AN, Prasad C. Hemolyticuremic syndrome (HUS) secondary to cobalamin C (Cbl-C)disorder.PediatrNephrol 2007; 22: 2097–103.

Shinnar S, Singer HS. Cobalamin C mutation (methylmalonic aciduria and homocystinuria) in adolescence. A treatable cause of dementia and myelopathy. N Engl J Med 1984; 311: 451-4.

Smith SE, Kinney HC, Swoboda KJ, Levy HL. Subacute combined degeneration of the spinal cord in cblC disorder despite treatment with B12. Mol Genet Metab 2006; 88: 138–45.

Thauvin-Robinet C, Roze E, Couvreur G, et al. The adolescent and adult form of cobalamin C disease: clinical and molecularspectrum. J Neurol Neurosurg Psychiatry 2008;79:725-8.

Tomaske M, Bosk A, Heinemann MK, et al. CblC/D defect combined with haemodynamically highly relevant VSD. J Inherit Metab Dis 2001; 24: 511-2.

Tsina EK, Marsden DL, Hansen RM, Fulton AB. Maculopathy and retinal degeneration in cobalamin C methylmalonic aciduria and homocystinuria. Arch Ophthalmol 2005; 123:1143-6.

Weintraub L, Tardo C, Rosenblatt D, Shapira E. Hydrocephalus as a possible complication of the CblS type of methylmalonic aciduria (Abstract). Am J Hum Genet 1991; 49: 108.

Weisfeld-Adams JD, Bender HA, Miley-Åkerstedt A, Frempong T, Schrager NL, Patel K, Naidich TP, Stein V, Spat J, Towns S, Wasserstein MP, Peter I, Frank Y, Diaz GA. Neurologic and

neurodevelopmental phenotypes in young children with early-treated combined methylmalonic acidemia and homocystinuria, cobalamin C type. Mol Genet Metab. 2013; 110:241-7.

Wu S, Gonzalez-Gomez I, Coates T, Yano S. Cobalamin C disease presenting with hemophagocytic lymphohistiocytosis. Pediatr Hematol Oncol 2005; 22: 717-21.

Legend to figures

Figure 1. Age of presentation in patients with the cblC defect.

Figure 2.General signs, neurological signs and ocular signs observed in patients with the cblC defect at onset (light bars) and during course (dark bars).SGA = Small for gestational age, HUS = haemolytic uremic

Table 1: Signs and symptoms in patients with CblC defect as reported in the literature

| *Frequent signs and symptoms*	*References*
• Feeding difficulties • Haematologic abnormalities • Hypotonia • Developmental delay • Seizures • Failure to thrive • Microcephaly • Pigmentary retinopathy • Decreased visual acuity • Nystagmus	Rosenblatt et al. 1997; Robb et al., 1984, Ricci et al., 2005; Weisfeld-Adams et al. 2013
Less frequently reported signs and symptoms	
Eye symptoms • retinal hypopigmentation • strabismus • optic atrophy • maculopathy	Mitchell et al., 1986;Tsina et al., 2005; Patton et al, 2000; Weisfeld-Adams et al. 2013
renal involvement including haemolytic uraemic syndrome	Gerarthy et al., 1992; Sharma et al., 2007
Dysmorphic features • macrocephaly • facial dysmorphism • marfanoid features	Cerone et al., 1999; Heil et al., 2007; Rosenblatt et al. 1997
Cardiopulmonary signs • congenital heart disease • cardiomyopathy and left ventricular non-compaction • cor pulmonale • pulmonary hypertension	Andersson et al. 1999; Brandstetter et al.1990; De Bie et al., 2009; Heinemann et al. 2001; Iodice et al. 2013; Longo et al. 2005; Ogier de Baulny et al., 1998; Profitlich et al., 2009; Tomaske et al., 2001
Neurological signs • neuropsychiatric disturbances • abnormal brain stem auditory and visual evoked potentials • white matter changes / atrophy • hydrocephalus • basal ganglia lesions • sensory peripheral neuropathy	Bianchieri et al., 2001; Bianchieri et al. 2002; Longo et al. 2005; Mamlock et al. 1986; Rosenblatt et al. 1997; Roze et al.2000; Smith et al., 2006; Weintraub et al., 1991; Weisfeld-Adams et al. 2013
Other presentations: • haemophagocytic lymphohistiocytosis • protein-losing enteropathy • neonatal hyperammonemia • acidosis • microthrombi • Thinned corpus callosum	Ellaway et al., 1998; Martinelli et al., 2011a; Rosenblatt et al. 1997; Weisfeld-Adams et al. 2013, Wu et al., 2005
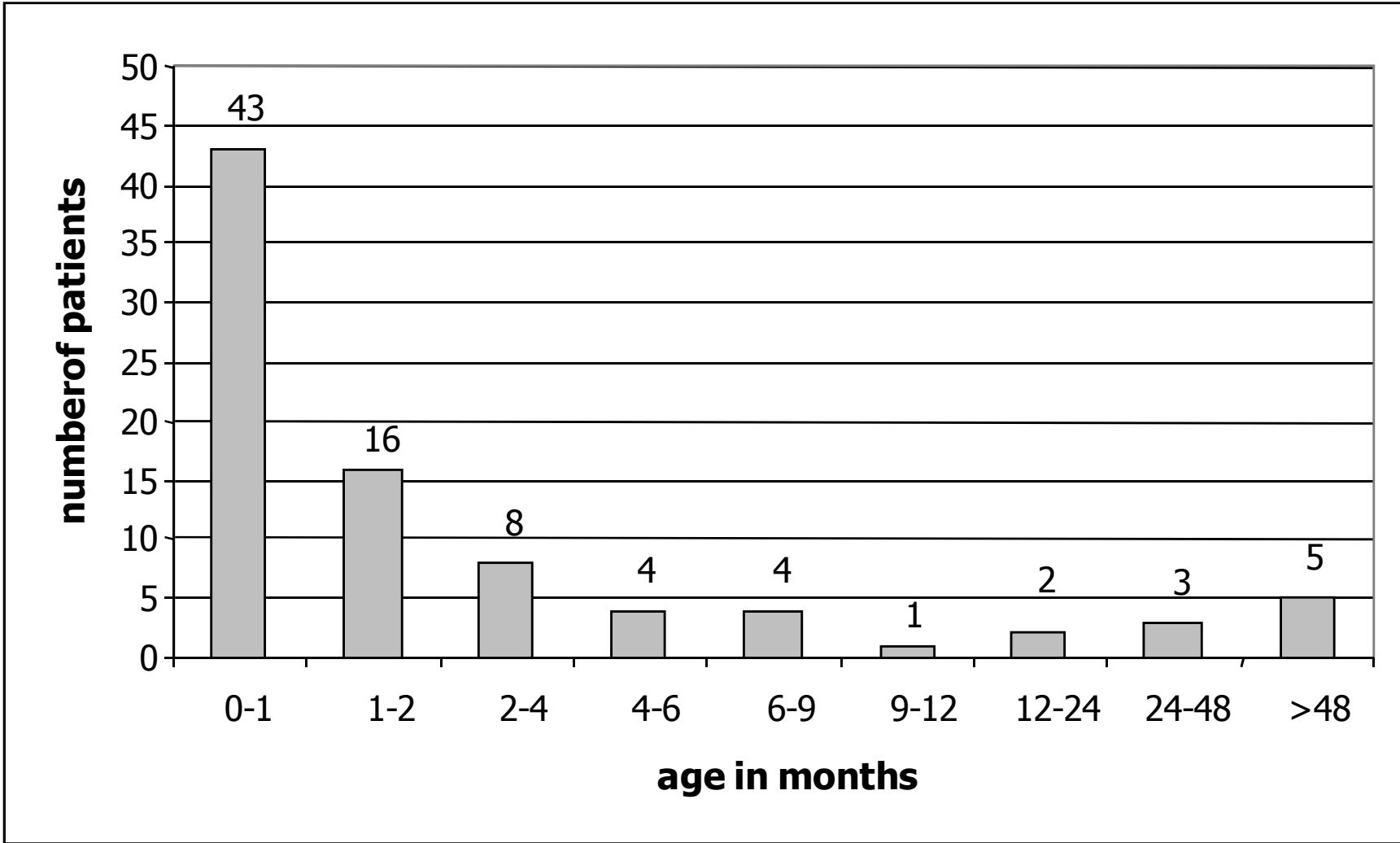
Figure 1
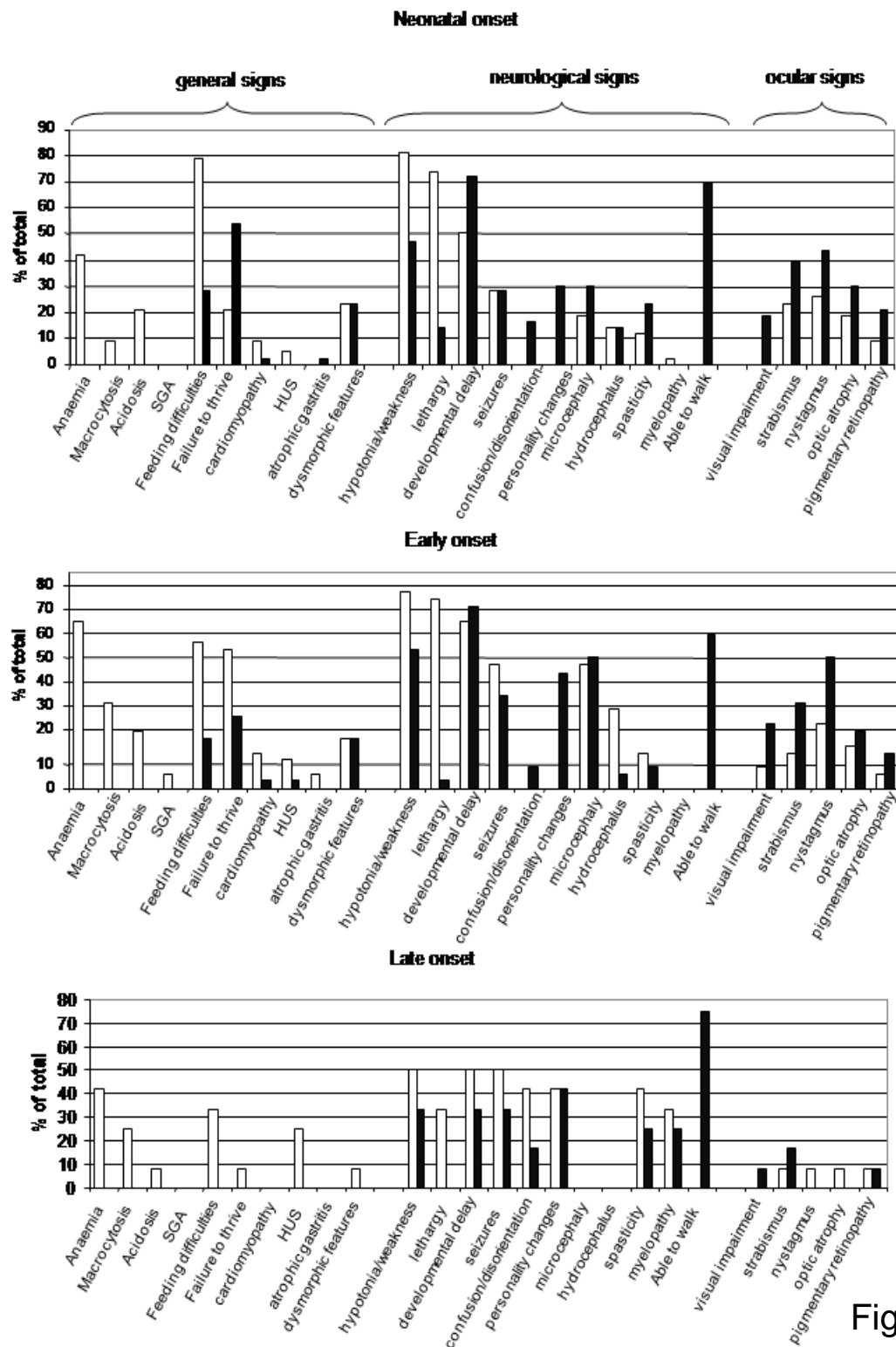
Figure 2

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