



HAL
open science

Sideroblastic anemia: molecular analysis of ALAS2 gene in a series of 29 probands and functional studies of ten missense mutations.

Sarah Ducamp, Caroline Kannengiesser, Mohamed Touati, Loïc Garçon, Agnès Guerci-Bresler, Jean-François Guichard, Christiane Vermylen, Joaquim Dochir, Hélène Antoine Poirel, Fanny Fouyssac, et al.

► To cite this version:

Sarah Ducamp, Caroline Kannengiesser, Mohamed Touati, Loïc Garçon, Agnès Guerci-Bresler, et al.. Sideroblastic anemia: molecular analysis of ALAS2 gene in a series of 29 probands and functional studies of ten missense mutations.. Human Mutation, 2011, 32 (6), pp.590. 10.1002/humu.21455 . hal-00616698

HAL Id: hal-00616698

<https://hal.science/hal-00616698>

Submitted on 24 Aug 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Sideroblastic anemia: molecular analysis of *ALAS2* gene in a series of 29 probands and functional studies of ten missense mutations.

Journal:	<i>Human Mutation</i>
Manuscript ID:	humu-2010-0359.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	30-Nov-2010
Complete List of Authors:	<p>Ducamp, Sarah; INSERM, CRB3, U773; AP-HP, Hôpital Louis Mourier, Centre Français des Porphyrries Kannengiesser, Caroline; AP-HP, Hôpital Bichat, genetics; INSERM, CRB3, U773 Touati, Mohamed; CHU Limoges, Hôpital Dupuytren, Hématologie clinique Garçon, Loïc; AP-HP, Hôpital Saint Antoine, Hématologie Biologique Guerci-Bresler, Agnès; CHU de Nancy, Hôpital Brabois, Hématologie Clinique Guichard, Jean-François; Hôpital Sainte Blandine, Médecine Interne-Pathologie Vasculaire - Immunologie Clinique Vermylen, Christiane; Clinique Universitaire Saint-Luc, de Duve Institute, UCL, Génétique Hématologique Dochir, Joaquim; Clinique Universitaire Saint-Luc, de Duve Institute, UCL, Génétique Hématologique Poirel, Hélène; Clinique Universitaire Saint-Luc, de Duve Institute, UCL, Génétique Hématologique Fouyssac, Fanny; CHU de Nancy, Hôpital Brabois, Hôpital d'Enfants, Hématologie Oncologique Mansuy, Ludovic; CHU de Nancy, Hôpital Brabois, Hôpital d'Enfants, Hématologie Oncologique Leroux, Geneviève; AP-HP, Hôpital Avicenne, Hématologie Tertian, Gérard; AP-HP, Hôpital Bicêtre, Hématologie Giro, Robert; AP-HP, Hôpital Tenon, Hématologie Biologique Heimpel, Hermann; Medizinische Universitätsklinik III Matthes, Thomas; HUG Genève, Hématologie Talbi, Neila; AP-HP, Hôpital Louis Mourier, Centre Français des Porphyrries Deybach, Jean-Charles; AP-HP, Hôpital Louis Mourier, Centre Français des Porphyrries Beaumont, Carole; INSERM, CRB3, U773 Puy, Hervé; INSERM, CRB3, U773; AP-HP, Hôpital Louis Mourier, Centre Français des Porphyrries</p>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

	Grandchamp, Bernard; INSERM, CRB3, U773; AP-HP, hôpital Bichat, genetics
Key Words:	X-linked Sideroblastic Anemia, ALAS2, heme synthesis, protoporphyrin

SCHOLARONE™
Manuscripts

For Peer Review

Title page**Title**

Sideroblastic anemia: molecular analysis of the *ALAS2* gene in a series of 29 probands and functional studies of ten missense mutations.

Authors

Sarah Ducamp^{1,2*}, Caroline Kannengiesser^{1,3*}, Mohamed Touati⁴, Loïc Garçon⁵, Agnès Guerci-Bresler⁶, Jean François Guichard⁷, Christiane Vermylen⁸, Joaquim Dochir⁸, Hélène A. Poirel⁸, Fanny Fouyssac⁹, Ludovic Mansuy⁹, Geneviève Leroux¹⁰, Gérard Tertian¹¹, Robert Girot¹², Hermann Heimpel¹³, Thomas Matthes¹⁴, Neila Talbi^{1,2}, Jean-Charles Deybach², Carole Beaumont¹, Hervé Puy^{1,2}, Bernard Grandchamp^{1,3}

Affiliation

1 - INSERM, Centre de Recherche Biomédicale Bichat-Beaujon, U773, Paris, F-75018, France

2 - Assistance Publique des Hôpitaux de Paris, Hôpital Louis Mourier, Centre Français des Porphyrines, Colombes, F-92701, France

3 - Assistance Publique des Hôpitaux de Paris, Hôpital Bichat, Laboratoire de Biochimie Hormonale et Génétique, Paris, F-75018, France

4 - CHU de Limoges, Hôpital Dupuytren, Hématologie clinique, Limoges, F-87042, France

5 - Assistance Publique des Hôpitaux de Paris, Hôpital Saint Antoine, Hématologie Biologique, Paris, F-75012, France

6 - CHU de Nancy, Hôpital Brabois, Hématologie Clinique, Vandoeuvre, F-54511, France

7 - Hôpital Sainte Blandine, Médecine Interne-Pathologie Vasculaire-immunologie clinique, Metz, F-57045, France

8 - Cliniques universitaires saint-Luc / de Duve Institute / UCL, Génétique Hématologique, Human Molecular Genetics (GEHU), Bruxelles, B-1200, Belgium

9 - CHU de Nancy, Hôpital Brabois - Hôpital d'Enfants, Hématologie Oncologie pédiatrique, Vandoeuvre F-54511, France

10 - Assistance Publique des Hôpitaux de Paris, Hôpital Avicenne, Hématologie, 125 route de Stalingrad, Bobigny, F-93009, France

11 - Assistance Publique des Hôpitaux de Paris CHU Bicêtre - Hématologie, Le Kremlin Bicêtre, F-94275, France

12 - Assistance Publique des Hôpitaux de Paris, Hôpital Tenon, hématologie biologique, Paris, F-75970, France

13 - Medizinische Universitätsklinik III, Ulm, D-89081, Germany

14 - HUG Genève, Service d'Hématologie, 1211 Genève, Switzerland

*both these authors participated equally to the work

Abstract

X-linked Sideroblastic Anemia (XLSA) is the most common genetic form of sideroblastic anemia, a heterogeneous group of disorders characterized by iron deposits in the mitochondria of erythroid precursors. XLSA is due to mutations in the erythroid-specific 5-aminolevulinate synthase (*ALAS2*) gene. Thirteen different *ALAS2* mutations were identified in 16 out of 29 probands with sideroblastic anemia. One third of the patients were females with a highly skewed X-chromosome inactivation. The identification of seven novel mutations in the *ALAS2* gene, six missense mutations, and one deletion in the proximal promoter extends the allelic heterogeneity of XLSA. Most of the missense mutations were predicted to be deleterious and ten of them, without any published functional characterization, were expressed in *E. coli*. *ALAS2* activities were assayed *in vitro*. Five missense mutations resulted in decreased enzymatic activity under standard conditions, and two other mutated proteins had decreased activity when assayed in the absence of exogenous pyridoxal phosphate and increased thermosensitivity. Although most amino-acid substitutions result in a clearly decreased enzymatic activity *in vitro*, a few mutations have a more subtle effect on the protein that is only revealed by *in vitro* tests under specific conditions.

Keys words

X-linked Sideroblastic Anemia, *ALAS2*, heme synthesis, protoporphyrin

Introduction

1
2
3
4
5
6
7
8 Congenital sideroblastic anemia (CSA) comprises a group of heterogeneous disorders
9 characterized by decreased heme synthesis and mitochondrial iron overload with ringed
10 sideroblasts in the bone marrow (For a review, see Camaschella, 2009). The most common
11 genetic form of CSA, X-linked Sideroblastic Anemia (XLSA, MIM# 300751), results from
12 mutations in the specific erythroid gene encoding 5-aminolevulinate synthase (*ALAS2*, also
13 known as *ALASE*, MIM *301300, EC 2.3.1.37) (Fleming, 2002) localized on chromosome
14 Xp11.21. ALAS is the first enzyme in the heme biosynthesis pathway and catalyzes the
15 condensation of glycine and succinyl-coenzyme A into 5-aminolevulinic acid (ALA), the
16 precursor of the tetrapyrroles (Gibson, et al., 1958; Shemin and Kikuchi, 1958). Pyridoxal 5'-
17 phosphate (PLP) is the cofactor of the enzyme. Most of the 48 reported *ALAS2* mutations
18 responsible for XLSA are missense mutations localized in exons 4 to 11 (Bergmann, et al.). A
19 variant in the proximal promoter was first reported as a mutation in an XLSA patient (Bekri,
20 et al., 2003), but this variant was subsequently found in unaffected individuals, leading to the
21 conclusion that it is a low frequency polymorphism and not a causal mutation (May A., 2005)
22 Most of these mutations were described at the genomic level without further characterization
23 of the mutated protein either *in vitro* or *in vivo*. In some patients, reduced ALAS enzymatic
24 activity has been reported in the bone marrow (Bottomley, et al., 1992; Cotter, et al., 1995;
25 Cox, et al., 1994; Harigae, et al., 1999a), and in others the mutated cDNA has been expressed
26 in *E. coli* in order to study the activity of mutated protein (Cotter, et al., 1992; Cotter, et al.,
27 1995; Cotter, et al., 1994; Cox, et al., 1994; Furuyama, et al., 1997; Furuyama, et al., 2006;
28 Furuyama, et al., 1998; Harigae, et al., 1999a; Harigae, et al., 1999b; Prades, et al., 1995). In
29 addition, in 2005, the crystallographic structure of *ALAS2* from *Rhodobacter capsulatus* (*R.*
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 *capsulatus*) was published, making it possible to map the XLSA causing mutations (Astner, et
4
5 al., 2005).
6

7
8 Here we report a series of 29 probands with SA. Thirteen different *ALAS2* mutations were
9
10 found in 16 probands. Seven of the 13 mutations had never previously been described,
11
12 including a 48-bp deletion in the proximal promoter region. The functional impact of the 12
13
14 remaining missense mutations was assessed *in silico* using bioinformatic tools. Moreover,
15
16 cDNAs were expressed in *E. coli* in order to assess the functional consequences of ten amino-
17
18 acid substitutions for six novel mutations and four previously reported but so far
19
20 uncharacterized mutations. *ALAS2* activity, enzyme thermosensitivity and pyridoxine
21
22 responsiveness were studied.
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Materials and Methods

Patients

We performed genetic analyses in 29 probands (17 males and 12 females) referred to our laboratory with a diagnosis of CSA based on the presence of sideroblasts in the bone marrow. Patients with syndromic or acquired forms of SA were excluded from this study. These patients originated from France, other Western European countries (Germany, Switzerland, Belgium) and Tunisia. Blood samples for genetic analysis were obtained from the patients or their parents after they had given signed informed consent in accordance with the requirements of the French Bioethics Committee “Agence of Biomedecine”. Hematological parameters had been evaluated by standard methods in the respective referring hospitals, and erythrocyte protoporphyrin was measured as previously described (Deacon and Elder, 2001).

X-inactivation study

Analysis of X chromosome inactivation was performed as previously described (Chollet-Martin et al., 2007) using the androgen receptor polymorphism as a marker.

Molecular analysis of the ALAS2 gene

Genomic DNA was extracted from peripheral blood using the QIAamp DNA blood Mini Kit (Qiagen, CA, USA). Analysis of the *ALAS2* gene (Genbank genomic: NG_008983.1, Genbank mRNA: NM_000032.4, Genbank protein: NP_000023.2) was performed by bidirectional direct sequencing. The 11 exons of *ALAS2*, the proximal promoter (250 bp) and the exon-intron junctions were amplified by PCR (Supp. Table S1). After purification of PCR products (PCR purification kit, Qiagen CA, USA), both strands were sequenced using a Big Dye Terminator Cycle Sequencing kit (Applied Biosystems, Life Technologies, Carlsbad, CA, USA). Sequencing products were purified (Sephadex G50, GE Healthcare, Piscataway,

1
2
3 NJ, USA), and analyzed using a 3130xl Genetic Analyzer (Applied Biosystems, Life
4
5 Technologies, Carlsbad, CA, USA) and the Seqscape analysis software (v2.6.0) (Applied
6
7 Biosystems, Life Technologies, Carlsbad, CA, USA). Identified mutations were confirmed on
8
9 a second sample, when available, or by family study. Numbering of *ALAS2* mutations
10
11 followed the international guidelines (www.hgvs.org/mutnomen). For the nucleotide
12
13 numbering, +1 corresponds to the A of the ATG translation initiation codon in the reference
14
15 sequence of the cDNA; for the amino acid numbering position 1 corresponds to the initiating
16
17 methionine.
18
19
20
21
22
23
24

25 ***In silico prediction of the functional impact of ALAS2 mutations***

26
27 The Grantham score (Grantham, 1974) and six bioinformatic tools were used *in silico* to
28
29 predict the impact of *ALAS2* mutations on protein structure or function, as previously
30
31 described (Kannengiesser, et al., 2009). The bioinformatic tools consisted of polyphen
32
33 (Sunyaev, et al., 2001), SIFT (Ng and Henikoff, 2003), SNP3D (Yue, et al., 2006),
34
35 PANTHER (Brunham, et al., 2005), UMD Predictor (Frederic, et al., 2009) and GVG
36
37 D (Tavtigian, et al., 2006).
38
39

40
41 To get an overall estimate of the impact of each mutation, we calculated a “prediction score”
42
43 from the number of programs that predicted that the alteration would be deleterious
44
45 (Grantham score >100; GVG D: C25-C65; PANTHER: highly/probably deleterious; SIFT:
46
47 affected; polyphen: damaging; UMD predictor: pathogenic; SNP3D: deleterious).
48
49
50
51
52
53
54
55
56
57
58
59
60

Localization of amino acids in Rhodobacter capsulatus

The localization of the mutated amino acids in the 3D structure of ALAS2 was predicted by sequence homology using the crystal structure of ALAS from *R. capsulatus* (PDB 2BWN, 2BWO and 2BWP) and Rasmol software (Sayle and Milner-White, 1995).

Expression of normal and mutant ALAS2 enzymes in E. coli

To investigate the effect of the mutations on ALAS2 activity, mutant enzymes were expressed in *E. coli* starting from a construct with the normal cDNA (pMALc2-AE2) kindly provided by Dr David Bishop (Cotter, et al., 1994). pMALc2-AE2 encodes a recombinant fusion protein consisting of a maltose binding protein (MBP, 387 AA) linked to the N-terminus of the mature human ALAS2 (509AA). We introduced the different mutations by site-directed mutagenesis using a Quick change kit (Stratagene, La Jolla, CA, USA) according to the manufacturer's instructions. The sequences of the mutagenesis primers are available upon request. The coding region of the resulting cDNAs was verified by sequencing.

Escherichia coli BL21 DE3 competent cells (Invitrogen, Life Technologies, Carlsbad, California, USA) were transformed with expression plasmids, and overnight cultures were grown in LB (Lennox L Broth Base, Invitrogen, Life Technologies, Carlsbad, California, USA) medium with 100 mg/ml ampicillin (PANPHARMA, Fougères - France). The next day, 20 ml of cultures in LB/ampicillin medium were initiated with the overnight cultures and grown to 1.2 A₆₀₀ units. ALAS2 synthesis was induced by adding 0.1 mM isopropyl b-D-thiogalactopyranoside (IPTG) in the presence of 0.5 mM 4,6-dioxoheptanoic acid (Sigma-Aldrich, St. Louis, MO, USA), also known as succinyl acetone, a strong inhibitor of the ALA dehydratase enzyme to prevent the transformation of ALA into porphyrins. Incubation was carried out in LB/ampicillin medium for 4 hr at 22°C. Cells were pelleted at 2500 rpm for 10 min, and then frozen at -80°C. The assay of ALAS2 activities of the control and mutant

1
2
3 enzymes under standard conditions was performed on crude bacterial lysates as previously
4 described (Lien and Beattie, 1982) with modifications. Pellets were sonicated in 300 μ l of
5 HEPES 50 mM pH 7.5 while maintained in ice. The total protein concentration was measured
6 by means of a protein assay (Bio-Rad Laboratories GmbH, Hercules, CA, USA), and the
7 samples were adjusted to a concentration of 0.2 mg of total protein/ml. Six hundred μ l of
8 samples were preincubated for 5 minutes at 37°C before the assay, then 100 μ l of a mixture
9 containing 1 mM Succinyl-CoA, 10 mM Glycine, 50 mM HEPES and 0.5 mM PLP (all from
10 Sigma-Aldrich, St. Louis, MO, USA) were added to samples. The reaction was stopped by
11 adding 60 μ l of 100% trichloroacetic acid either immediately (T0) or after 20 minutes (T20)
12 at 37°C. The reaction product 5-aminolevulinate (ALA) was quantified by colorimetry, after a
13 reaction of ALA with acetyl acetone (Fluka analytical, Sigma-Aldrich, St. Louis, MO, USA)
14 (Mauzerall and Granick, 1956). The ALA pyrroles were not separated from other pyrroles
15 present in the bacterial lysate before adding Erlich's reagent. Instead, the ALA synthesized
16 during the incubation was calculated from the OD obtained with Erlich's reaction after
17 subtracting a blank corresponding to the OD obtained with the lysate from a bacterial clone
18 expressing the ALAS2 C344X mutant. This mutant encodes a truncated protein shown to be
19 devoid of enzymatic activity by the lack of difference in OD between T0 and T20 (data not
20 shown). We checked that all bacterial lysates corresponding to wild type and mutant
21 recombinant ALAS2 (including the C344X mutant) yielded identical OD values at T0.
22

23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48 The specific activity (S_A) was expressed in pmol of ALA/mg total protein at 37°C. The
49 residual activity (%) was determined by expressing the specific activity of mutants relative to
50 that of the wild type ALAS2.
51

52
53
54
55
56
57
58
59
60
In some cases, specific assay conditions were used consisting of either omitting PLP from the
incubation mixture or preincubating the bacterial lysate at 37°C for 30 or 60 minutes instead
of 5 minutes. The significance of the results was estimated using Student's t-test.

Immunoblotting

2.5 μg of total protein of the supernatant from bacteria lysates were taken up onto 1X Laemmli buffer, and heated for 10 minutes at 100°C. Samples were analysed by SDS-PAGE using an 8% polyacrylamide gel followed by electro-transfer on a polyvinylidene fluoride (PVDF) membrane. Loading and transfer were confirmed by Ponceau red staining. After pre-incubation in blocking solution (7% skimmed milk in Tween 20 in Tris buffered saline, TBST 0,15%) overnight at 4°C, the membrane was incubated with an anti-MBP antiserum (1/20 000, E8030S, New England Biolabs, Ozyme, Ipswich, MA, USA) for 2H at room temperature. After washing three times with TBST for 10 minutes each time, the membrane was incubated with a secondary anti rabbit IgG, linked to Horseradish peroxidase (1/20 000, Amersham GE Healthcare, Piscataway, NJ, USA) for 2H at room temperature. The MBP fusion proteins were visualized (Immobilon Western, chemiluminescent HRP substrate, Millipore Corporation, Billerica, MA, USA) according to the Manufacturer's instructions.

Results

Twenty-nine patients with a diagnosis of CSA were referred to our laboratory for molecular exploration. All of them had ringed sideroblasts in the bone marrow, and most of them had mild to severe anemia at the time of referral. The *ALAS2* gene was sequenced. Thirteen different mutations, including 12 substitutions and 1 deletion, were identified in 16 probands (10 males and 6 females). Table 1 summarizes clinical data for patients carrying an *ALAS2* mutation.

Five of the six affected females had highly skewed X inactivation consistent with a diagnosis of XLSA (data not shown). The remaining affected female (proband 8) was not informative for the androgen receptor polymorphism.

Six of these mutations had already been reported (Bottomley, 2004; Bottomley, et al., 1995; Goncalves, et al., 2004; May and Bishop, 1998), whereas the other seven had not been described before (Harigae and Furuyama). Twelve of these 13 mutations caused amino acid substitutions (Table 1), and the thirteenth was a 48-bp deletion (c.-91_-44del) in the proximal promoter (Table 1 and Figure 1). This deletion led to the removal of the TATA-like box localized between -82 and -76 bp upstream of the translational initiating codon (Cox, et al., 1991) and of the first 9 nucleotides of exon 1. A rare P520L variant, previously reported as a putative modifier of iron overload with an allelic frequency of 0.0013 in Caucasians (Lee, et al., 2006), was found in one female proband (number 13, Table 1) in the absence of any other sequence variation.

Erythrocyte protoporphyrin concentration was measured in six patients carrying an *ALAS2* mutation (Table 1). In all XLSA cases, the protoporphyrin concentration was within the normal range of values (less than 1.9 μ moles/L of red blood cells).

1
2
3 We used various different *in silico* software products to predict the functional consequences
4 of the *ALAS2* missense mutations. All the substitutions were predicted to be deleterious, apart
5 from R218H and E242K (Supp. Table S2).
6
7

8
9
10 To assess *in vitro* the functional consequences of ten amino acid substitutions that had not
11 been studied before (ten missense mutations corresponding to six novel mutations and four
12 previously reported mutations without functional data) we expressed the mutant cDNAs in
13 *E. coli*. Immunoblotting was performed to confirm that the expression level of recombinant
14 normal and mutant proteins were similar (Supp. Figure S1). When the enzymatic activity was
15 assayed from *E. coli* lysates immediately after cell disruption, five *ALAS2* mutants (E242K,
16 D263N, P339L, R375C, R411H) displayed significantly reduced *ALAS2* activity, with
17 residual activity ranging between 14 and 65 % of the normal construct (Figure 2 and Table 2).
18
19 Expression of the remaining five mutated cDNAs (R170H, R218H, R452G, P520L and
20 R572H) resulted in the production of a protein with an enzymatic activity that was no
21 different from that of the normal construct.
22
23
24
25
26
27
28
29
30
31
32
33
34

35
36 For four mutants, we also measured the activity of the protein in the absence of added
37 exogenous PLP (Figure 3a). R170H and R218H mutants displayed significantly reduced
38 activity in this situation, whereas neither R452H nor R572H did. We also tested the thermal
39 stability of these four mutated enzymes by pre-incubating them at 37°C for 30 or 60 minutes
40 prior to the enzymatic assay (Figure 3b). Once again, the R170H and R218H mutants
41 displayed significantly increased thermosensitivity, while the R452H and R572H mutants did
42 not significantly differ from the wild type. Adding exogenous PLP to the preincubation
43 medium prevented the loss of activity induced by preincubating at 37°C for all the mutants as
44 well as for the normal enzyme (data not shown).
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Discussion

The results reported here for a series of 29 probands with CSA highlights a number of interesting points regarding the genetic heterogeneity of the disease and the functional consequences of *ALAS2* mutations. *ALAS2* variants were found in 16 out of the 29 probands, including a P520L variant previously reported as being a rare polymorphism (Lee, et al., 2006). Recently, other gene defects have been identified in autosomal recessive forms of CSA (MIM #205950): a homozygous mutation was found in *GLRX5* in a consanguineous proband (Camaschella, et al., 2007), and *SLC25A38* which encodes a putative glycine transporter, was found to be mutated in the affected members of different families (Guernsey, et al., 2009). Thus for the 13 probands without any *ALAS2* mutation, and for one patient with the P520L variant, these two genes were explored and mutations were identified in *SLC25A38* for four probands (manuscript submitted). No variant was identified in any of the three genes explored in the other 9 patients; the characteristics available for these patients are reported in Suppl. table S3). This proportion is similar to that reported by Bergmann et al. (Bergmann, et al., 2010), suggesting that other loci must be involved.

Our data extend the allelic heterogeneity of XSLA, since we identified seven novel mutations including a deletion in the proximal promoter region, in addition to five mutations already known. As expected, XLSA symptomatic heterozygous females displayed highly skewed X-chromosome inactivation (Aivado, et al., 2006; Cazzola, et al., 2000).

We clearly show that a defect in the first step of the heme biosynthetic pathway prevents the abnormal accumulation of erythrocyte protoporphyrin both in patients with *ALAS2* mutations (Table 1) as well as in one patient with the *SLC25A38* mutation (data not shown). Therefore, this simple measurement may provide a useful screening test before sequencing *ALAS2* and *SLC25A38*. Indeed, elevated erythrocyte protoporphyrin levels have been described in other anemic syndromes, including many types of CSA linked to *ABCB7*, *SLC19A2* or

1
2
3 mitochondrial defects (Camaschella, 2009). Furthermore, erythrocyte samples were available
4
5 for three unexplained cases of CSA (without any identified mutations of *ALAS2* or
6
7 *SLC25A38*) out of the 14 in our series. In contrast to the XLSA patients, they had an elevated
8
9 level of erythrocyte protoporphyrin (>1.9 $\mu\text{moles/L}$ red blood cells, data not shown).
10
11

12 Finally, we addressed the functional consequences of *ALAS2* mutations in order to evaluate
13
14 their deleterious impact. The deletion in the proximal promoter of the *ALAS2* gene led to the
15
16 elimination of the TATA-like motif and the first 9 bp of exon 1. The TATA-like motif has
17
18 been shown to be functionally important by mutagenesis studies (Surinya, et al., 1997). It is
19
20 likely that some other sequence upstream of the deletion may act as a weak promoter, since
21
22 *ALAS2* mRNA was detected at a lower concentration in the bone marrow of the male patient
23
24 15 than in unrelated controls (data not shown). The complete loss of *ALAS2* expression is
25
26 probably lethal, as shown by the absence of *ALAS2*-null embryos following specific
27
28 disruption of *ALAS2* gene in mice (Nakajima, et al., 1999).
29
30
31
32

33 The finding of a previously reported variant P520L as the only sequence variation in a
34
35 proband female with a highly skewed pattern of X-inactivation raises the question of the
36
37 possible relevance of this mutation. However, expression studies of the P520L cDNA failed
38
39 to reveal any functional impact.
40
41
42

43 The functional consequence of the six novel missense mutations was evaluated by studying
44
45 the enzymatic activity of the recombinant mutant protein expressed in *E. coli*. Three
46
47 previously reported mutants, for which such data were not available, were also studied
48
49 (Table 1). A significant decrease in the enzymatic activity measured *in vitro* was evidenced
50
51 for five mutants: E242K, D263N, P339L, R375C and R411H (Table 3). The histidine
52
53 substitution at position 411 (R411H mutation) decreased *ALAS2* activity to the same extent
54
55 as the cysteine substitution previously reported (Furuyama, et al., 1998).
56
57
58
59
60

1
2
3 For four other mutations (R170H, R218H, R452H, R572H), *in vitro* activity was not different
4
5 from the wild type control under standard conditions. Two of these mutants (R170H and
6
7 R218H) showed reduced activity in the absence of exogenous PLP and increased
8
9 thermosensitivity. This may be explained by reduced affinity for PLP and higher sensitivity
10
11 to thermal denaturing of the apoenzyme as compared to the holoenzyme, the proportion of the
12
13 two forms being modified by the presence of added PLP. These results are consistent with the
14
15 structural analysis of ALAS from *R. capsulatus* leading to the prediction that the substitution
16
17 of the R170 would affect the binding of PLP (Astner, et al., 2005). However, the patient with
18
19 the R170H mutation did not respond to PLP therapy. Because *in silico* tools did not predict
20
21 any deleterious impact for R218H, and because both this mutant and the R170H mutant
22
23 behaved similarly in our functional studies, we localized the corresponding positions on the
24
25 quaternary structure of *R. capsulatus* (see Supp. Figure S2). Interestingly, A75 (at a position
26
27 homologous to that of R218 in humans) in one monomer is quite close to R28 (at homologous
28
29 position to human R170) on the other monomer, suggesting the possibility that these two
30
31 amino acids may be important for the dimerization of ALAS2.
32
33

34
35 Finally, two mutated proteins, R452G and R572H, did not differ from the wild type in the *in*
36
37 *vitro* system despite damaging *in silico* predictions. These two mutants were as active and as
38
39 thermostable as the normal enzyme. Similar findings had previously been reported for other
40
41 mutations, including R452C and R452H (Furuyama, et al., 2006). Although the R452G and
42
43 R572H mutants did not display loss-of-function in *E. coli*, several lines of evidence support
44
45 their implication in XLSA. The CGC codon encoding R452 is a hot spot for mutations. This
46
47 arginine R452 has been found to be substituted in approximately one-quarter of patients with
48
49 XLSA (Furuyama, et al., 2006). In our series, R452C occurred in two independent probands.
50
51 Two independent probands were also carrier of the R572H mutation and one of them, for
52
53 whom blood sample was available, showed an erythrocyte protoporphyrin concentration at the
54
55
56
57
58
59
60

1
2
3 lower end of the normal range. These observations suggest that R452G and R572H are causal
4 mutations. We can hypothesize the implication of additional factors in the bone marrow or a
5 defective enzyme processing as has been suggested for K299Q and D190V, previously
6 reported to display normal activities (Cotter, et al., 1995; Furuyama, et al., 1997).
7
8
9

10
11
12 As previously reported, iron overload may be a major complication of XLSA, and the iron
13 depletion by either iron chelators or phlebotomy (Camaschella, 2008) not only effectively
14 prevents the deleterious effects of iron overload, but also improves erythropoiesis.
15
16
17

18
19
20 A correlation between these “milder” defects and the phenotype of the patients remains
21 speculative, given the known intrafamilial variability of XSLA. It is noteworthy that the
22 patient with R452G has a mild anemia, and the two patients with the R572H mutations have
23 near-to-normal hemoglobin levels, microcytosis and a relatively late onset of the disease. It is
24 interesting to note the wide variability in the degree of anemia in patients with *ALAS2*
25 mutations, ranging from a baby boy with a very severe form of the disease requiring repeated
26 blood transfusions (patient 3, see Table1), to patients with mild microcytosis diagnosed at age
27 46 and 57 respectively (patients 14 and 15, see Table1). In these last two cases, the diagnosis
28 was suspected because of iron overload in absence of transfusion, and confirmed by bone
29 marrow examination revealing the presence of ringed sideroblasts.
30
31
32
33
34
35
36
37
38
39
40
41
42

43
44 In conclusion, we confirm in a large cohort of patients that about half of the cases of non
45 syndromic sideroblastic anemia are accounted for by *ALAS2* mutations, and that a high degree
46 of clinical heterogeneity parallels the diversity of the mutations and of their functional
47 consequences.
48
49
50
51
52
53
54
55
56
57
58
59
60

Acknowledgments

We would like to thank David Bishop for the gift of the *ALAS2* wild type plasmid, Jérôme Lamoril and Vasco Da Silva for their helpful discussions, Yolande Kroviarski, Nathalie Clément, Anne Marie Robréau, Gilles Hetet, Claire Oudin, Dominique Henry, Sylvie Simonin for their technical assistance, and Vincent Oustric for his help with the Rasmol software. The research was funded by Agence Nationale de la Recherche (ANR 07-MRAR-008-03).

For Peer Review

References

- 1
2
3
4
5
6
7
8 Aivado M, Gattermann N, Rong A, Giagounidis AA, Prall WC, Czibere A, Hildebrandt B,
9 Haas R, Bottomley SS. 2006. X-linked sideroblastic anemia associated with a novel
10 ALAS2 mutation and unfortunate skewed X-chromosome inactivation patterns. *Blood*
11 *Cells Mol Dis* 37(1):40-5.
12
13 Astner I, Schulze JO, van den Heuvel J, Jahn D, Schubert WD, Heinz DW. 2005. Crystal
14 structure of 5-aminolevulinate synthase, the first enzyme of heme biosynthesis, and its
15 link to XLSA in humans. *EMBO J* 24(18):3166-77.
16
17 Bekri S, May A, Cotter PD, Al-Sabah AI, Guo X, Masters GS, Bishop DF. 2003. A promoter
18 mutation in the erythroid-specific 5-aminolevulinate synthase (ALAS2) gene causes
19 X-linked sideroblastic anemia. *Blood* 102(2):698-704.
20
21 Bergmann AK, Campagna DR, McLoughlin EM, Agarwal S, Fleming MD, Bottomley SS,
22 Neufeld EJ. Systematic molecular genetic analysis of congenital sideroblastic anemia:
23 evidence for genetic heterogeneity and identification of novel mutations. *Pediatr*
24 *Blood Cancer* 54(2):273-8.
25
26 Bottomley SS. 2004. Sideroblastic anemias. Philadelphia Lippincott Williams & Wilkins.
27 Bottomley SS, Healy HM, Brandenburg MA, May BK. 1992. 5-Aminolevulinate synthase in
28 sideroblastic anemias: mRNA and enzyme activity levels in bone marrow cells. *Am J*
29 *Hematol* 41(2):76-83.
30
31 Bottomley SS, May BK, Cox TC, Cotter PD, Bishop DF. 1995. Molecular defects of
32 erythroid 5-aminolevulinate synthase in X-linked sideroblastic anemia. *J Bioenerg*
33 *Biomembr* 27(2):161-8.
34
35 Brunham LR, Singaraja RR, Pape TD, Kejariwal A, Thomas PD, Hayden MR. 2005.
36 Accurate prediction of the functional significance of single nucleotide polymorphisms
37 and mutations in the ABCA1 gene. *PLoS Genet* 1(6):e83.
38
39 Camaschella C. 2008. Recent advances in the understanding of inherited sideroblastic
40 anaemia. *Br J Haematol* 143(1):27-38.
41
42 Camaschella C. 2009. Hereditary sideroblastic anemias: pathophysiology, diagnosis, and
43 treatment. *Semin Hematol* 46(4):371-7.
44
45 Camaschella C, Campanella A, De Falco L, Boschetto L, Merlini R, Silvestri L, Levi S,
46 Iolascon A. 2007. The human counterpart of zebrafish shiraz shows sideroblastic-like
47 microcytic anemia and iron overload. *Blood* 110(4):1353-8.
48
49 Cazzola M, May A, Bergamaschi G, Cerani P, Rosti V, Bishop DF. 2000. Familial-skewed X-
50 chromosome inactivation as a predisposing factor for late-onset X-linked sideroblastic
51 anemia in carrier females. *Blood* 96(13):4363-5.
52
53 Cotter PD, Baumann M, Bishop DF. 1992. Enzymatic defect in "X-linked" sideroblastic
54 anemia: molecular evidence for erythroid delta-aminolevulinate synthase deficiency.
55 *Proc Natl Acad Sci U S A* 89(9):4028-32.
56
57 Cotter PD, May A, Fitzsimons EJ, Houston T, Woodcock BE, al-Sabah AI, Wong L, Bishop
58 DF. 1995. Late-onset X-linked sideroblastic anemia. Missense mutations in the
59 erythroid delta-aminolevulinate synthase (ALAS2) gene in two pyridoxine-responsive
60 patients initially diagnosed with acquired refractory anemia and ringed sideroblasts. *J*
Clin Invest 96(4):2090-6.
61
62 Cotter PD, Rucknagel DL, Bishop DF. 1994. X-linked sideroblastic anemia: identification of
63 the mutation in the erythroid-specific delta-aminolevulinate synthase gene (ALAS2) in
64 the original family described by Cooley. *Blood* 84(11):3915-24.

- 1
2
3 Cox TC, Bawden MJ, Martin A, May BK. 1991. Human erythroid 5-aminolevulinate
4 synthase: promoter analysis and identification of an iron-responsive element in the
5 mRNA. *EMBO J* 10(7):1891-902.
- 6
7 Cox TC, Bottomley SS, Wiley JS, Bawden MJ, Matthews CS, May BK. 1994. X-linked
8 pyridoxine-responsive sideroblastic anemia due to a Thr388-to-Ser substitution in
9 erythroid 5-aminolevulinate synthase. *N Engl J Med* 330(10):675-9.
- 10
11 Deacon AC, Elder GH. 2001. ACP Best Practice No 165: front line tests for the investigation
12 of suspected porphyria. *J Clin Pathol* 54(7):500-7.
- 13
14 Edgar AJ, Vidyatilake HM, Wickramasinghe SN. 1998. X-linked sideroblastic anaemia due to
15 a mutation in the erythroid 5-aminolaevulinate synthase gene leading to an
16 arginine170 to leucine substitution. *Eur J Haematol* 61(1):55-8.
- 17
18 Fleming MD. 2002. The genetics of inherited sideroblastic anemias. *Semin Hematol*
19 39(4):270-81.
- 20
21 Frederic MY, Lalande M, Boileau C, Hamroun D, Claustres M, Beroud C, Collod-Beroud G.
22 2009. UMD-predictor, a new prediction tool for nucleotide substitution pathogenicity -
23 - application to four genes: FBN1, FBN2, TGFBR1, and TGFBR2. *Hum Mutat*
24 30(6):952-9.
- 25
26 Furuyama K, Fujita H, Nagai T, Yomogida K, Munakata H, Kondo M, Kimura A, Kuramoto
27 A, Hayashi N, Yamamoto M. 1997. Pyridoxine refractory X-linked sideroblastic
28 anemia caused by a point mutation in the erythroid 5-aminolevulinate synthase gene.
29 *Blood* 90(2):822-30.
- 30
31 Furuyama K, Harigae H, Heller T, Hamel BC, Minder EI, Shimizu T, Kuribara T, Blijlevens
32 N, Shibahara S, Sassa S. 2006. Arg452 substitution of the erythroid-specific 5-
33 aminolaevulinate synthase, a hot spot mutation in X-linked sideroblastic anaemia,
34 does not itself affect enzyme activity. *Eur J Haematol* 76(1):33-41.
- 35
36 Furuyama K, Sassa S. 2002. Multiple mechanisms for hereditary sideroblastic anemia. *Cell*
37 *Mol Biol (Noisy-le-grand)* 48(1):5-10.
- 38
39 Furuyama K, Uno R, Urabe A, Hayashi N, Fujita H, Kondo M, Sassa S, Yamamoto M. 1998.
40 R411C mutation of the ALAS2 gene encodes a pyridoxine-responsive enzyme with
41 low activity. *Br J Haematol* 103(3):839-41.
- 42
43 Gibson KD, Laver WG, Neuberger A. 1958. Initial stages in the biosynthesis of porphyrins. 2.
44 The formation of delta-aminolaevulinic acid from glycine and succinyl-coenzyme A by
45 particles from chicken erythrocytes. *Biochem J* 70(1):71-81.
- 46
47 Goncalves P, Pereira JC, Ribeiro ML. 2004. Gene symbol: ALAS2. Disease: sideroblastic
48 anaemia. *Hum Genet* 115(6):532.
- 49
50 Grantham R. 1974. Amino acid difference formula to help explain protein evolution. *Science*
51 185(4154):862-4.
- 52
53 Guernsey DL, Jiang H, Campagna DR, Evans SC, Ferguson M, Kellogg MD, Lachance M,
54 Matsuoka M, Nightingale M, Rideout A and others. 2009. Mutations in mitochondrial
55 carrier family gene SLC25A38 cause nonsyndromic autosomal recessive congenital
56 sideroblastic anemia. *Nat Genet* 41(6):651-3.
- 57
58 Harigae H, Furuyama K. Hereditary sideroblastic anemia: pathophysiology and gene
59 mutations. *Int J Hematol* 92(3):425-31.
- 60
61 Harigae H, Furuyama K, Kimura A, Neriishi K, Tahara N, Kondo M, Hayashi N, Yamamoto
62 M, Sassa S, Sasaki T. 1999a. A novel mutation of the erythroid-specific delta-
63 aminolaevulinate synthase gene in a patient with X-linked sideroblastic anaemia. *Br J*
64 *Haematol* 106(1):175-7.
- 65
66 Harigae H, Furuyama K, Kudo K, Hayashi N, Yamamoto M, Sassa S, Sasaki T. 1999b. A
67 novel mutation of the erythroid-specific gamma-Aminolevulinate synthase gene in a

- 1
2
3 patient with non-inherited pyridoxine-responsive sideroblastic anemia. *Am J Hematol*
4 62(2):112-4.
5
6 Kannengiesser C, Brookes S, del Arroyo AG, Pham D, Bombled J, Barrois M, Mauffret O,
7 Avril MF, Chompret A, Lenoir GM and others. 2009. Functional, structural, and
8 genetic evaluation of 20 CDKN2A germ line mutations identified in melanoma-prone
9 families or patients. *Hum Mutat* 30(4):564-74.
10
11 Lee PL, Barton JC, Rao SV, Acton RT, Adler BK, Beutler E. 2006. Three kinships with
12 ALAS2 P520L (c. 1559 C --> T) mutation, two in association with severe iron
13 overload, and one with sideroblastic anemia and severe iron overload. *Blood Cells*
14 *Mol Dis* 36(2):292-7.
15
16 Lien LF, Beattie DS. 1982. Comparisons and modifications of the colorimetric assay for
17 delta-aminolevulinic acid synthase. *Enzyme* 28(2-3):120-32.
18
19 Mauzerall D, Granick S. 1956. The occurrence and determination of delta-amino-levulinic
20 acid and porphobilinogen in urine. *J Biol Chem* 219(1):435-46.
21
22 May A, Bishop DF. 1998. The molecular biology and pyridoxine responsiveness of X-linked
23 sideroblastic anaemia. *Haematologica* 83(1):56-70.
24
25 May A. BC, Masters G., Kingston J., Lawless S., and Jenner M. . 2005. Severe Sideroblastic
26 Anaemia in an ALAS2 Compound Heterozygote for -206G, a Common Polymorphism,
27 and a Novel Mutation in Exon 11 (Lys535del) Linked to Lack of Haemoglobinisation
28 In Vitro and Ineffective Erythropoiesis In Vivo. *Blood (ASH Annual Meeting*
29 *Abstracts)* 106:3541.
30
31 Nakajima O, Takahashi S, Harigae H, Furuyama K, Hayashi N, Sassa S, Yamamoto M. 1999.
32 Heme deficiency in erythroid lineage causes differentiation arrest and cytoplasmic
33 iron overload. *EMBO J* 18(22):6282-9.
34
35 Ng PC, Henikoff S. 2003. SIFT: Predicting amino acid changes that affect protein function.
36 *Nucleic Acids Res* 31(13):3812-4.
37
38 Prades E, Chambon C, Dailey TA, Dailey HA, Briere J, Grandchamp B. 1995. A new
39 mutation of the ALAS2 gene in a large family with X-linked sideroblastic anemia.
40 *Hum Genet* 95(4):424-8.
41
42 Sayle RA, Milner-White EJ. 1995. RASMOL: biomolecular graphics for all. *Trends Biochem*
43 *Sci* 20(9):374.
44
45 Shemin D, Kikuchi G. 1958. Enzymatic synthesis of sigma-aminolevulinic acid. *Ann N Y*
46 *Acad Sci* 75(1):122-8.
47
48 Sunyaev S, Ramensky V, Koch I, Lathe W, 3rd, Kondrashov AS, Bork P. 2001. Prediction of
49 deleterious human alleles. *Hum Mol Genet* 10(6):591-7.
50
51 Surinya KH, Cox TC, May BK. 1997. Transcriptional regulation of the human erythroid 5-
52 aminolevulinic acid synthase gene. Identification of promoter elements and role of
53 regulatory proteins. *J Biol Chem* 272(42):26585-94.
54
55 Tavgigian SV, Deffenbaugh AM, Yin L, Judkins T, Scholl T, Samollow PB, de Silva D,
56 Zharkikh A, Thomas A. 2006. Comprehensive statistical study of 452 BRCA1
57 missense substitutions with classification of eight recurrent substitutions as neutral. *J*
58 *Med Genet* 43(4):295-305.
59
60 Yue P, Melamud E, Moulton J. 2006. SNPs3D: candidate gene and SNP selection for
association studies. *BMC Bioinformatics* 7:166.

Figure Legends

Figure 1: Hemizygous deletion of 48 base pairs in the proximal promoter of *ALAS2* gene

A: PCR amplification of the promoter region from a normal control (lane 1; expected size 627 bp); male proband 15 (lane 2; shorter PCR product of 579 bp) and his mother (lane 3; healthy carrier); M: DNA molecular weight markers (Fermentas, 100 bp ladder);

B: Sequence of the proximal promoter of the *ALAS2* gene (Adapted from Cox, et al., 1991) showing the TATA-like box (in bold), the beginning of exon 1 (underlined), and the deletion (underlined in gray)

Figure 2: Residual activities of the various different recombinant *ALAS2* mutant enzymes assayed under standard conditions

The residual activity of each mutant is expressed as a percentage of the normal enzyme activity as described in Material and Methods. Enzyme activity was measured on at least 3 independent bacterial cultures. The statistical significance of comparisons of the specific activities between each mutant and the normal enzyme was established using Student's t-test (*: p value < 0.05). Five mutants (E242K, D263N P339L, R375C and R411H) display significant loss-of-function.

Figure 3: PLP-dependence and thermosensitivity of the recombinant normal and mutant *ALAS2*

A/ The specific activity of wild type enzyme and four mutant enzymes (R170H, R218H, R452G and R572H, showing no loss-of-function under standard conditions) was measured without adding PLP to the assay, as described in Material and Methods. Specific activities are expressed in pmoles of ALA produced by mg protein after subtracting the specific activity of C344X (negative control). The statistical significance of the comparisons between each

1
2
3 mutant and the normal enzyme was established using Student-s t-test (*: p value < 0.05). Two
4
5 mutants (R170H and R218H) display PLP sensitivity.
6
7

8 B/ The specific activity of wild type enzyme and four mutant enzymes (R170H, R218H,
9
10 R452G and R572H) was measured after preincubating for 30 or 60 minutes before the assay,
11
12 as described in Material and Methods. The statistical significance of comparisons between
13
14 each mutant and the normal enzyme was established using Student's t-test (*: p value < 0.05).
15
16

17 Two mutants (R170H and R218H) are thermosensitive.
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

Title page**Title**

Sideroblastic anemia: molecular analysis of the *ALAS2* gene in a series of 29 probands and functional studies of ten missense mutations.

Authors

Sarah Ducamp^{1,2*}, Caroline Kannengiesser^{1,3*}, Mohamed Touati⁴, Loïc Garçon⁵, Agnès Guerci-Bresler⁶, Jean François Guichard⁷, Christiane Vermylen⁸, Joaquim Dochir⁸, **Hélène A. Poirel⁸**, Fanny Fouyssac⁹, Ludovic Mansuy⁹, Geneviève Leroux¹⁰, Gérard Tertian¹¹, Robert Giro¹², Hermann Heimpel¹³, Thomas Matthes¹⁴, Neila Talbi^{1,2}, Jean-Charles Deybach², Carole Beaumont¹, Hervé Puy^{1,2}, Bernard Grandchamp^{1,3}

Formatted: Highlight

Affiliation

1 - INSERM, Centre de Recherche Biomédicale Bichat-Beaujon, U773, Paris, F-75018, France

2 - Assistance Publique des Hôpitaux de Paris, Hôpital Louis Mourier, Centre Français des Porphyries, Colombes, F-92701, France

3 - Assistance Publique des Hôpitaux de Paris, Hôpital Bichat, Laboratoire de Biochimie Hormonale et Génétique, Paris, F-75018, France

4 - CHU de Limoges, Hôpital Dupuytren, Hématologie clinique, Limoges, F-87042, France

5 - Assistance Publique des Hôpitaux de Paris, Hôpital Saint Antoine, Hématologie Biologique, Paris, F-75012, France

6 - CHU de Nancy, Hôpital Brabois, Hématologie Clinique, Vandoeuvre, F-54511, France

7 - Hôpital Sainte Blandine, Médecine Interne-Pathologie Vasculaire-immunologie clinique, Metz, F-57045, France

8 - Cliniques universitaires saint-Luc / de Duve Institute / UCL, Génétique Hématologique, Human Molecular Genetics (GEHU), Bruxelles, B-1200, Belgium

9 - CHU de Nancy, Hôpital Brabois - Hôpital d'Enfants, Hématologie Oncologie pédiatrique, Vandoeuvre F-54511, France

10 - Assistance Publique des Hôpitaux de Paris, Hôpital Avicenne, Hématologie, 125 route de Stalingrad, Bobigny, F-93009, France

11 - Assistance Publique des Hôpitaux de Paris CHU Bicêtre - Hématologie, Le Kremlin Bicêtre, F-94275, France

12 - Assistance Publique des Hôpitaux de Paris, Hôpital Tenon, hématologie biologique, Paris, F-75970, France

13 - Medizinische Universitätsklinik III, Ulm, D-89081, Germany

14 - HUG Genève, Service d'Hématologie, 1211 Genève, Switzerland

*both these authors participated equally to the work

Abstract

X-linked Sideroblastic Anemia (XLSA) is the most common genetic form of sideroblastic anemia, a heterogeneous group of disorders characterized by iron deposits in the mitochondria of erythroid precursors. XLSA is due to mutations in the erythroid-specific 5-aminolevulinate synthase (*ALAS2*) gene. Thirteen different *ALAS2* mutations were identified in 16 out of 29 probands with sideroblastic anemia. One third of the patients were females with a highly skewed X-chromosome inactivation. The identification of seven novel mutations in the *ALAS2* gene, six missense mutations, and one deletion in the proximal promoter extends the allelic heterogeneity of XLSA. Most of the missense mutations were predicted to be deleterious and ten of them, without any published functional characterization, were expressed in *E. coli*. *ALAS2* activities were assayed *in vitro*. Five missense mutations resulted in decreased enzymatic activity under standard conditions, and two other mutated proteins had decreased activity when assayed in the absence of exogenous pyridoxal phosphate and increased thermosensitivity. Although most amino-acid substitutions result in a clearly decreased enzymatic activity *in vitro*, a few mutations have a more subtle effect on the protein that is only revealed by *in vitro* tests under specific conditions.

Formatted: Highlight

Formatted: Highlight

Keys words

X-linked Sideroblastic Anemia, *ALAS2*, heme synthesis, protoporphyrin

Introduction

Congenital sideroblastic anemia (CSA) comprises a group of heterogeneous disorders

Formatted: Highlight

characterized by decreased heme synthesis and mitochondrial iron overload with ringed sideroblasts in the bone marrow (For a review, see Camaschella, 2009). The most common genetic form of CSA, X-linked Sideroblastic Anemia (XLSA, MIM# 300751), results from mutations in the specific erythroid gene encoding 5-aminolevulinate synthase (*ALAS2*, also

known as *ALASE*, **MIM *301300, EC 2.3.1.37**) (Fleming, 2002) localized on chromosome

Formatted: Highlight

Xp11.21. ALAS is the first enzyme in the heme biosynthesis pathway and catalyzes the condensation of glycine and succinyl-coenzyme A into 5-aminolevulinic acid (ALA), the precursor of the tetrapyrroles (Gibson, et al., 1958; Shemin and Kikuchi, 1958). Pyridoxal 5'-phosphate (PLP) is the cofactor of the enzyme. Most of the 48 reported *ALAS2* mutations

responsible for XLSA are missense mutations localized in exons 4 to 11 (Bergmann, et al.). **A**

Formatted: Highlight

variant in the proximal promoter was first reported as a mutation in an XLSA patient (Bekri,

et al., 2003), but this variant was subsequently found in unaffected individuals, leading to the

conclusion that it is a low frequency polymorphism and not a causal mutation (May A., 2005).

Most of these mutations were described at the genomic level without further characterization of the mutated protein either *in vitro* or *in vivo*. In some patients, reduced ALAS enzymatic activity has been reported in the bone marrow (Bottomley, et al., 1992; Cotter, et al., 1995; Cox, et al., 1994; Harigae, et al., 1999a), and in others the mutated cDNA has been expressed in *E. coli* in order to study the activity of mutated protein (Cotter, et al., 1992; Cotter, et al., 1995; Cotter, et al., 1994; Cox, et al., 1994; Furuyama, et al., 1997; Furuyama, et al., 2006; Furuyama, et al., 1998; Harigae, et al., 1999a; Harigae, et al., 1999b; Prades, et al., 1995). In addition, in 2005, the crystallographic structure of *ALAS2* from *Rhodobacter capsulatus* (*R.*

1
2 *capsulatus*) was published, making it possible to map the XLSA causing mutations (Astner, et
3
4 al., 2005).

5
6 Here we report a series of 29 probands with SA. Thirteen different *ALAS2* mutations were
7
8 found in 16 probands. Seven of the 13 mutations had never previously been described,
9
10 including a 48-bp deletion in the proximal promoter region. The functional impact of the 12
11
12 remaining missense mutations was assessed *in silico* using bioinformatic tools. Moreover,
13
14 cDNAs were expressed in *E. coli* in order to assess the functional consequences of ten amino-
15
16 acid substitutions for six novel mutations and four previously reported but so far
17
18 uncharacterized mutations. *ALAS2* activity, enzyme thermosensitivity and pyridoxine
19
20 responsiveness were studied.
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

Materials and Methods

Patients

We performed genetic analyses in 29 probands (17 males and 12 females) referred to our laboratory with a diagnosis of CSA based on the presence of sideroblasts in the bone marrow. Patients with syndromic or acquired forms of SA were excluded from this study. These patients originated from France, other Western European countries (Germany, Switzerland, Belgium) and Tunisia. Blood samples for genetic analysis were obtained from the patients or their parents after they had given signed informed consent in accordance with the requirements of the French Bioethics Committee “Agence of Biomedecine”. Hematological parameters had been evaluated by standard methods in the respective referring hospitals, and erythrocyte protoporphyrin was measured as previously described (Deacon and Elder, 2001).

Formatted: Highlight

X-inactivation study

Analysis of X chromosome inactivation was performed as previously described (Chollet-Martin et al., 2007) using the androgen receptor polymorphism as a marker.

Molecular analysis of the ALAS2 gene

Genomic DNA was extracted from peripheral blood using the QIAamp DNA blood Mini Kit (Qiagen, CA, USA). Analysis of the ALAS2 gene (Genbank genomic: NG_008983.1, Genbank mRNA: NM_000032.4, Genbank protein: NP_000023.2) was performed by bidirectional direct sequencing. The 11 exons of ALAS2, the proximal promoter (250 bp) and the exon-intron junctions were amplified by PCR (Supp. Table S1). After purification of PCR products (PCR purification kit, Qiagen CA, USA), both strands were sequenced using a Big Dye Terminator Cycle Sequencing kit (Applied Biosystems, Life Technologies, Carlsbad, CA, USA). Sequencing products were purified (Sephadex G50, GE Healthcare, Piscataway,

Formatted: Highlight

1
2 NJ, USA), and analyzed using a 3130xl Genetic Analyzer (Applied Biosystems, Life
3 Technologies, Carlsbad, CA, USA) and the Seqscape analysis software (v2.6.0) (Applied
4 Biosystems, Life Technologies, Carlsbad, CA, USA). Identified mutations were confirmed on
5 a second sample, when available, or by family study. Numbering of *ALAS2* mutations
6 followed the international guidelines (www.hgvs.org/mutnomen). For the nucleotide
7 numbering, +1 corresponds to the A of the ATG translation initiation codon in the reference
8 sequence of the cDNA; for the amino acid numbering position 1 corresponds to the initiating
9 methionine.

Formatted: Highlight

In silico prediction of the functional impact of ALAS2 mutations

10
11
12
13
14
15
16
17
18
19
20
21
22 The Grantham score (Grantham, 1974) and six bioinformatic tools were used *in silico* to
23 predict the impact of *ALAS2* mutations on protein structure or function, as previously
24 described (Kannengiesser, et al., 2009). The bioinformatic tools consisted of polyphen
25 (Sunyaev, et al., 2001), SIFT (Ng and Henikoff, 2003), SNP3D (Yue, et al., 2006),
26 PANTHER (Brunham, et al., 2005), UMD Predictor (Frederic, et al., 2009) and GVG
27 D (Tavtigian, et al., 2006).

28
29
30
31
32
33 To get an overall estimate of the impact of each mutation, we calculated a “prediction score”
34 from the number of programs that predicted that the alteration would be deleterious
35 (Grantham score >100; GVG D: C25-C65; PANTHER: highly/probably deleterious; SIFT:
36 affected; polyphen: damaging; UMD predictor: pathogenic; SNP3D: deleterious).
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Localization of amino acids in Rhodobacter capsulatus

The localization of the mutated amino acids in the 3D structure of ALAS2 was predicted by sequence homology using the crystal structure of ALAS from *R. capsulatus* (PDB 2BWN, 2BWO and 2BWP) and Rasmol software (Sayle and Milner-White, 1995).

Expression of normal and mutant ALAS2 enzymes in E. coli

To investigate the effect of the mutations on ALAS2 activity, mutant enzymes were expressed in *E. coli* starting from a construct with the normal cDNA (pMALc2-AE2) kindly provided by Dr David Bishop (Cotter, et al., 1994). pMALc2-AE2 encodes a recombinant fusion protein consisting of a maltose binding protein (MBP, 387 AA) linked to the N-terminus of the mature human ALAS2 (509AA). We introduced the different mutations by site-directed mutagenesis using a Quick change kit (Stratagene, La Jolla, CA, USA) according to the manufacturer's instructions. The sequences of the mutagenesis primers are available upon request. The coding region of the resulting cDNAs was verified by sequencing.

Escherichia coli BL21 DE3 competent cells (Invitrogen, Life Technologies, Carlsbad, California, USA) were transformed with expression plasmids, and overnight cultures were grown in LB (Lennox L Broth Base, Invitrogen, Life Technologies, Carlsbad, California, USA) medium with 100 mg/ml ampicillin (PANPHARMA, Fougères - France). The next day, 20 ml of cultures in LB/ampicillin medium were initiated with the overnight cultures and grown to 1.2 A₆₀₀ units. ALAS2 synthesis was induced by adding 0.1 mM isopropyl b-D-thiogalactopyranoside (IPTG) in the presence of 0.5 mM 4,6-dioxoheptanoic acid (Sigma-Aldrich, St. Louis, MO, USA), also known as succinyl acetone, a strong inhibitor of the ALA dehydratase enzyme to prevent the transformation of ALA into porphyrins. Incubation was carried out in LB/ampicillin medium for 4 hr at 22°C. Cells were pelleted at 2500 rpm for 10 min, and then frozen at -80°C. The assay of ALAS2 activities of the control and mutant

Formatted: Highlight

1 enzymes under standard conditions was performed on crude bacterial lysates as previously
2 described (Lien and Beattie, 1982) with modifications. Pellets were sonicated in 300 μ l of
3 HEPES 50 mM pH 7.5 while maintained in ice. The total protein concentration was measured
4 by means of a protein assay (Bio-Rad Laboratories GmBh, Hercules, CA, USA), and the
5 samples were adjusted to a concentration of 0.2 mg of total protein/ml. Six hundred μ l of
6 samples were preincubated for 5 minutes at 37°C before the assay, then 100 μ l of a mixture
7 containing 1 mM Succinyl-CoA, 10 mM Glycine, 50 mM HEPES and 0.5 mM PLP (all from
8 Sigma-Aldrich, St. Louis, MO, USA) were added to samples. The reaction was stopped by
9 adding 60 μ l of 100% trichloroacetic acid either immediately (T0) or after 20 minutes (T20)
10 at 37°C. The reaction product 5-aminolevulinate (ALA) was quantified by colorimetry, after a
11 reaction of ALA with acetyl acetone (Fluka analytical, Sigma-Aldrich, St. Louis, MO, USA)
12 (Mauzerall and Granick, 1956).

13 **The ALA pyrroles were not separated from other pyrroles**
14 **present in the bacterial lysate before adding Erlich's reagent. Instead, the ALA synthesized**
15 **during the incubation was calculated from the OD obtained with Erlich's reaction after**
16 **subtracting a blank corresponding to the OD obtained with the lysate from a bacterial clone**
17 **expressing the ALAS2 C344X mutant. This mutant encodes a truncated protein shown to be**
18 **devoid of enzymatic activity by the lack of difference in OD between T0 and T20 (data not**
19 **shown). We checked that all bacterial lysates corresponding to wild type and mutant**
20 **recombinant ALAS2 (including the C344X mutant) yielded identical OD values at T0.**

Formatted: Highlight

21 The specific activity (S_A) was expressed in pmol of ALA/mg total protein at 37°C. The
22 residual activity (%) was determined by expressing the specific activity of mutants relative to
23 that of the wild type ALAS2.

24 In some cases, specific assay conditions were used consisting of either omitting PLP from the
25 incubation mixture or preincubating the bacterial lysate at 37°C for 30 or 60 minutes instead
26 of 5 minutes. The significance of the results was estimated using Student's t-test.

Immunoblotting

2.5 µg of total protein of the supernatant from bacteria lysates were taken up onto 1X Laemmli buffer, and heated for 10 minutes at 100°C. Samples were analysed by SDS-PAGE using an 8% polyacrylamide gel followed by electro-transfer on a polyvinylidene fluoride (PVDF) membrane. Loading and transfer were confirmed by Ponceau red staining. After pre-incubation in blocking solution (7% skimmed milk in Tween 20 in Tris buffered saline, TBST 0,15%) overnight at 4°C, the membrane was incubated with an anti-MBP antiserum (1/20 000, E8030S, New England Biolabs, Ozyme, Ipswich, MA, USA) for 2H at room temperature. After washing three times with TBST for 10 minutes each time, the membrane was incubated with a secondary anti rabbit IgG, linked to Horseradish peroxidase (1/20 000, Amersham GE Healthcare, Piscataway, NJ, USA) for 2H at room temperature. The MBP fusion proteins were visualized (Immobilon Western, chemiluminescent HRP substrate, Millipore Corporation, Billerica, MA, USA) according to the Manufacturer's instructions.

Results

Twenty-nine patients with a diagnosis of CSA were referred to our laboratory for molecular exploration. All of them had ringed sideroblasts in the bone marrow, and most of them had mild to severe anemia at the time of referral. The *ALAS2* gene was sequenced. Thirteen different mutations, including 12 substitutions and 1 deletion, were identified in 16 probands (10 males and 6 females). Table 1 summarizes clinical data for patients carrying an *ALAS2* mutation.

Five of the six affected females had highly skewed X inactivation consistent with a diagnosis of XLSA (data not shown). The remaining affected female (proband 8) was not informative for the androgen receptor polymorphism.

Six of these mutations had already been reported (Bottomley, 2004; Bottomley, et al., 1995; Goncalves, et al., 2004; May and Bishop, 1998), whereas the other seven had not been described before (Harigae and Furuyama). Twelve of these 13 mutations caused amino acid substitutions (Table 1), and the thirteenth was a 48-bp deletion (c.-91_-44del) in the proximal promoter (Table 1 and Figure 1). This deletion led to the removal of the TATA-like box localized between -82 and -76 bp upstream of the translational initiating codon (Cox, et al., 1991) and of the first 9 nucleotides of exon 1. A rare P520L variant, previously reported as a putative modifier of iron overload with an allelic frequency of 0.0013 in Caucasians (Lee, et al., 2006), was found in one female proband (number 13, Table 1) in the absence of any other sequence variation.

Erythrocyte protoporphyrin concentration was measured in six patients carrying an *ALAS2* mutation (Table 1). In all XLSA cases, the protoporphyrin concentration was within the normal range of values (less than 1.9 μ moles/L of red blood cells).

Formatted: Highlight

1 We used various different *in silico* software products to predict the functional consequences
2 of the *ALAS2* missense mutations. All the substitutions were predicted to be deleterious, apart
3 from R218H and E242K (Supp. Table S2).
4

Formatted: Highlight

5
6
7
8 To assess *in vitro* the functional consequences of ten amino acid substitutions that had not
9 been studied before (ten missense mutations corresponding to six novel mutations and four
10 previously reported mutations without functional data) we expressed the mutant cDNAs in
11

Formatted: Highlight

12 *E. coli*. Immunoblotting was performed to confirm that the expression level of recombinant
13 normal and mutant proteins were similar (Supp. Figure S1). When the enzymatic activity was
14 assayed from *E. coli* lysates immediately after cell disruption, five *ALAS2* mutants (E242K,
15 D263N, P339L, R375C, R411H) displayed significantly reduced *ALAS2* activity, with
16 residual activity ranging between 14 and 65 % of the normal construct (Figure 2 and Table 2).
17
18 Expression of the remaining five mutated cDNAs (R170H, R218H, R452G, P520L and
19 R572H) resulted in the production of a protein with an enzymatic activity that was no
20 different from that of the normal construct.
21

22 For four mutants, we also measured the activity of the protein in the absence of added
23 exogenous PLP (Figure 3a). R170H and R218H mutants displayed significantly reduced
24 activity in this situation, whereas neither R452H nor R572H did. We also tested the thermal
25 stability of these four mutated enzymes by pre-incubating them at 37°C for 30 or 60 minutes
26 prior to the enzymatic assay (Figure 3b). Once again, the R170H and R218H mutants
27 displayed significantly increased thermosensitivity, while the R452H and R572H mutants did
28 not significantly differ from the wild type. Adding exogenous PLP to the preincubation
29 medium prevented the loss of activity induced by preincubating at 37°C for all the mutants as
30 well as for the normal enzyme (data not shown).
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Discussion

The results reported here for a series of 29 probands with CSA highlights a number of interesting points regarding the genetic heterogeneity of the disease and the functional consequences of *ALAS2* mutations. *ALAS2* variants were found in 16 out of the 29 probands, including a P520L variant previously reported as being a rare polymorphism (Lee, et al., 2006). Recently, other gene defects have been identified in autosomal recessive forms of CSA (MIM #205950): a homozygous mutation was found in *GLRX5* in a consanguineous proband (Camaschella, et al., 2007), and *SLC25A38* which encodes a putative glycine transporter, was found to be mutated in the affected members of different families (Guernsey, et al., 2009). Thus for the 13 probands without any *ALAS2* mutation, and for one patient with the P520L variant, these two genes were explored and mutations were identified in *SLC25A38* for four probands (manuscript submitted). No variant was identified in any of the three genes explored in the other 9 patients; the characteristics available for these patients are reported in Suppl. table S3). This proportion is similar to that reported by Bergmann et al. (Bergmann, et al., 2010), suggesting that other loci must be involved.

Our data extend the allelic heterogeneity of XSLA, since we identified seven novel mutations including a deletion in the proximal promoter region, in addition to five mutations already known. As expected, XLSA symptomatic heterozygous females displayed highly skewed X-chromosome inactivation (Aivado, et al., 2006; Cazzola, et al., 2000).

We clearly show that a defect in the first step of the heme biosynthetic pathway prevents the abnormal accumulation of erythrocyte protoporphyrin both in patients with *ALAS2* mutations (Table 1) as well as in one patient with the *SLC25A38* mutation (data not shown). Therefore, this simple measurement may provide a useful screening test before sequencing *ALAS2* and *SLC25A38*. Indeed, elevated erythrocyte protoporphyrin levels have been described in other anemic syndromes, including many types of CSA linked to *ABCB7*, *SLC19A2* or

Formatted: Highlight

Formatted: Highlight

1
2 mitochondrial defects (Camaschella, 2009). Furthermore, erythrocyte samples were available
3
4 for three unexplained cases of CSA (without any identified mutations of *ALAS2* or
5
6 *SLC25A38*) out of the 14 in our series. In contrast to the XLSA patients, they had an elevated
7
8 level of erythrocyte protoporphyrin (>1.9 μmoles/L red blood cells, data not shown).

9
10 Finally, we addressed the functional consequences of *ALAS2* mutations in order to evaluate
11
12 their deleterious impact. The deletion in the proximal promoter of the *ALAS2* gene led to the
13
14 elimination of the TATA-like motif and the first 9 bp of exon 1. **The TATA-like motif has**
15
16 **been shown to be functionally important by mutagenesis studies (Surinya, et al., 1997).** It is
17
18 likely that some other sequence upstream of the deletion may act as a weak promoter, since
19
20 *ALAS2* mRNA was detected at a lower concentration in the bone marrow of the male patient
21
22 15 than in unrelated controls (data not shown). The complete loss of *ALAS2* expression is
23
24 probably lethal, as shown by the absence of *ALAS2*-null embryos following specific
25
26 disruption of *ALAS2* gene in mice (Nakajima, et al., 1999).

27
28 The finding of a previously reported variant P520L as the only sequence variation in a
29
30 proband female with a highly skewed pattern of X-inactivation raises the question of the
31
32 possible relevance of this mutation. However, expression studies of the P520L cDNA failed
33
34 to reveal any functional impact.

35
36 The functional consequence of the six novel missense mutations was evaluated by studying
37
38 the enzymatic activity of the recombinant mutant protein expressed in *E. coli*. Three
39
40 previously reported mutants, for which such data were not available, were also studied
41
42 (Table 1). A significant decrease in the enzymatic activity measured *in vitro* was evidenced
43
44 for five mutants: E242K, D263N, P339L, R375C and R411H (Table 3). The histidine
45
46 substitution at position 411 (R411H mutation) decreased *ALAS2* activity to the same extent
47
48 as the cysteine substitution previously reported (Furuyama, et al., 1998).

Formatted: Highlight

1
2 For four other mutations (R170H, R218H, R452H, R572H), *in vitro* activity was not different
3
4 from the wild type control under standard conditions. Two of these mutants (R170H and
5
6 R218H) showed reduced activity in the absence of exogenous PLP and increased
7
8 thermosensitivity. This may be explained by reduced affinity for PLP and higher sensitivity
9
10 to thermal denaturing of the apoenzyme as compared to the holoenzyme, the proportion of the
11
12 two forms being modified by the presence of added PLP. These results are consistent with the
13
14 structural analysis of ALAS from *R. capsulatus* leading to the prediction that the substitution
15
16 of the R170 would affect the binding of PLP (Astner, et al., 2005). However, the patient with
17
18 the R170H mutation did not respond to PLP therapy. Because *in silico* tools did not predict
19
20 any deleterious impact for R218H, and because both this mutant and the R170H mutant
21
22 behaved similarly in our functional studies, we localized the corresponding positions on the
23
24 quaternary structure of *R. capsulatus* (see Supp. Figure S2). Interestingly, A75 (at a position
25
26 homologous to that of R218 in humans) in one monomer is quite close to R28 (at homologous
27
28 position to human R170) on the other monomer, suggesting the possibility that these two
29
30 amino acids may be important for the dimerization of ALAS2.

31
32 Finally, two mutated proteins, R452G and R572H, did not differ from the wild type in the *in*
33
34 *vitro* system despite damaging *in silico* predictions. These two mutants were as active and as
35
36 thermostable as the normal enzyme. Similar findings had previously been reported for other
37
38 mutations, including R452C and R452H (Furuyama, et al., 2006). Although the R452G and
39
40 R572H mutants did not display loss-of-function in *E. coli*, several lines of evidence support
41
42 their implication in XLSA. The CGC codon encoding R452 is a hot spot for mutations. This
43
44 arginine R452 has been found to be substituted in approximately one-quarter of patients with
45
46 XLSA (Furuyama, et al., 2006). In our series, R452C occurred in two independent probands.
47
48 Two independent probands were also carrier of the R572H mutation and one of them, for
49
50 whom blood sample was available, showed an erythrocyte protoporphyrin concentration at the
51
52
53
54
55
56
57
58
59
60

1
2 lower end of the normal range. These observations suggest that R452G and R572H are causal
3
4 mutations. We can hypothesize the implication of additional factors in the bone marrow or a
5
6 defective enzyme processing as has been suggested for K299Q and D190V, previously
7
8 reported to display normal activities (Cotter, et al., 1995; Furuyama, et al., 1997).
9

10 As previously reported, iron overload may be a major complication of XLSA, and the iron
11
12 depletion by either iron chelators or phlebotomy (Camaschella, 2008) not only effectively
13
14 prevents the deleterious effects of iron overload, but also improves erythropoiesis.
15

16 A correlation between these “milder” defects and the phenotype of the patients remains
17
18 speculative, given the known intrafamilial variability of XSLA. It is noteworthy that the
19
20 patient with R452G has a mild anemia, and the two patients with the R572H mutations have
21
22 near-to-normal hemoglobin levels, microcytosis and a relatively late onset of the disease. It is
23
24 interesting to note the wide variability in the degree of anemia in patients with *ALAS2*
25
26 mutations, ranging from a baby boy with a very severe form of the disease requiring repeated
27
28 blood transfusions (patient 3, see Table1), to patients with mild microcytosis diagnosed at age
29
30 46 and 57 respectively (patients 14 and 15, see Table1). In these last two cases, the diagnosis
31
32 was suspected because of iron overload in absence of transfusion, and confirmed by bone
33
34 marrow examination revealing the presence of ringed sideroblasts.
35

36 In conclusion, we confirm in a large cohort of patients that about half of the cases of non
37
38 syndromic sideroblastic anemia are accounted for by *ALAS2* mutations, and that a high degree
39
40 of clinical heterogeneity parallels the diversity of the mutations and of their functional
41
42 consequences.
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2 **Acknowledgments**
3

4 We would like to thank David Bishop for the gift of the *ALAS2* wild type plasmid, Jérôme
5 Lamoril and Vasco Da Silva for their helpful discussions, Yolande Kroviarski, Nathalie
6 Clément, Anne Marie Robréau, Gilles Hetet, Claire Oudin, Dominique Henry, Sylvie Simonin
7
8 for their technical assistance, and Vincent Oustric for his help with the Rasmol software. The
9
10 research was funded by Agence Nationale de la Recherche (ANR 07-MRAR-008-03).
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

References

- 1
2
3
4
5
6 Aivado M, Gattermann N, Rong A, Giagounidis AA, Prall WC, Czibere A, Hildebrandt B,
7 Haas R, Bottomley SS. 2006. X-linked sideroblastic anemia associated with a novel
8 ALAS2 mutation and unfortunate skewed X-chromosome inactivation patterns. *Blood*
9 *Cells Mol Dis* 37(1):40-5.
- 10 Astner I, Schulze JO, van den Heuvel J, Jahn D, Schubert WD, Heinz DW. 2005. Crystal
11 structure of 5-aminolevulinate synthase, the first enzyme of heme biosynthesis, and its
12 link to XLSA in humans. *EMBO J* 24(18):3166-77.
- 13 Bekri S, May A, Cotter PD, Al-Sabah AI, Guo X, Masters GS, Bishop DF. 2003. A promoter
14 mutation in the erythroid-specific 5-aminolevulinate synthase (ALAS2) gene causes
15 X-linked sideroblastic anemia. *Blood* 102(2):698-704.
- 16 Bergmann AK, Campagna DR, McLoughlin EM, Agarwal S, Fleming MD, Bottomley SS,
17 Neufeld EJ. Systematic molecular genetic analysis of congenital sideroblastic anemia:
18 evidence for genetic heterogeneity and identification of novel mutations. *Pediatr*
19 *Blood Cancer* 54(2):273-8.
- 20 Bottomley SS. 2004. Sideroblastic anemias. Philadelphia Lippincott Williams & Wilkins.
- 21 Bottomley SS, Healy HM, Brandenburg MA, May BK. 1992. 5-Aminolevulinate synthase in
22 sideroblastic anemias: mRNA and enzyme activity levels in bone marrow cells. *Am J*
23 *Hematol* 41(2):76-83.
- 24 Bottomley SS, May BK, Cox TC, Cotter PD, Bishop DF. 1995. Molecular defects of
25 erythroid 5-aminolevulinate synthase in X-linked sideroblastic anemia. *J Bioenerg*
26 *Biomembr* 27(2):161-8.
- 27 Brunham LR, Singaraja RR, Pape TD, Kejariwal A, Thomas PD, Hayden MR. 2005.
28 Accurate prediction of the functional significance of single nucleotide polymorphisms
29 and mutations in the ABCA1 gene. *PLoS Genet* 1(6):e83.
- 30 Camaschella C. 2008. Recent advances in the understanding of inherited sideroblastic
31 anaemia. *Br J Haematol* 143(1):27-38.
- 32 Camaschella C. 2009. Hereditary sideroblastic anemias: pathophysiology, diagnosis, and
33 treatment. *Semin Hematol* 46(4):371-7.
- 34 Camaschella C, Campanella A, De Falco L, Boschetto L, Merlini R, Silvestri L, Levi S,
35 Iolascon A. 2007. The human counterpart of zebrafish shiraz shows sideroblastic-like
36 microcytic anemia and iron overload. *Blood* 110(4):1353-8.
- 37 Cazzola M, May A, Bergamaschi G, Cerani P, Rosti V, Bishop DF. 2000. Familial-skewed X-
38 chromosome inactivation as a predisposing factor for late-onset X-linked sideroblastic
39 anemia in carrier females. *Blood* 96(13):4363-5.
- 40 Cotter PD, Baumann M, Bishop DF. 1992. Enzymatic defect in "X-linked" sideroblastic
41 anemia: molecular evidence for erythroid delta-aminolevulinate synthase deficiency.
42 *Proc Natl Acad Sci U S A* 89(9):4028-32.
- 43 Cotter PD, May A, Fitzsimons EJ, Houston T, Woodcock BE, al-Sabah AI, Wong L, Bishop
44 DF. 1995. Late-onset X-linked sideroblastic anemia. Missense mutations in the
45 erythroid delta-aminolevulinate synthase (ALAS2) gene in two pyridoxine-responsive
46 patients initially diagnosed with acquired refractory anemia and ringed sideroblasts. *J*
47 *Clin Invest* 96(4):2090-6.
- 48 Cotter PD, Rucknagel DL, Bishop DF. 1994. X-linked sideroblastic anemia: identification of
49 the mutation in the erythroid-specific delta-aminolevulinate synthase gene (ALAS2) in
50 the original family described by Cooley. *Blood* 84(11):3915-24.
- 51
52
53
54
55
56
57
58
59
60

- 1
2 Cox TC, Bawden MJ, Martin A, May BK. 1991. Human erythroid 5-aminolevulinat
3 synthase: promoter analysis and identification of an iron-responsive element in the
4 mRNA. *EMBO J* 10(7):1891-902.
- 5 Cox TC, Bottomley SS, Wiley JS, Bawden MJ, Matthews CS, May BK. 1994. X-linked
6 pyridoxine-responsive sideroblastic anemia due to a Thr388-to-Ser substitution in
7 erythroid 5-aminolevulinat synthase. *N Engl J Med* 330(10):675-9.
- 8 Deacon AC, Elder GH. 2001. ACP Best Practice No 165: front line tests for the investigation
9 of suspected porphyria. *J Clin Pathol* 54(7):500-7.
- 10 Edgar AJ, Vidyatilake HM, Wickramasinghe SN. 1998. X-linked sideroblastic anaemia due to
11 a mutation in the erythroid 5-aminolaevulinat synthase gene leading to an
12 arginine170 to leucine substitution. *Eur J Haematol* 61(1):55-8.
- 13 Fleming MD. 2002. The genetics of inherited sideroblastic anemias. *Semin Hematol*
14 39(4):270-81.
- 15 Frederic MY, Lalande M, Boileau C, Hamroun D, Claustres M, Beroud C, Collod-Beroud G.
16 2009. UMD-predictor, a new prediction tool for nucleotide substitution pathogenicity -
17 - application to four genes: FBN1, FBN2, TGFBR1, and TGFBR2. *Hum Mutat*
18 30(6):952-9.
- 19 Furuyama K, Fujita H, Nagai T, Yomogida K, Munakata H, Kondo M, Kimura A, Kuramoto
20 A, Hayashi N, Yamamoto M. 1997. Pyridoxine refractory X-linked sideroblastic
21 anemia caused by a point mutation in the erythroid 5-aminolevulinat synthase gene.
22 *Blood* 90(2):822-30.
- 23 Furuyama K, Harigae H, Heller T, Hamel BC, Minder EI, Shimizu T, Kuribara T, Blijlevens
24 N, Shibahara S, Sassa S. 2006. Arg452 substitution of the erythroid-specific 5-
25 aminolaevulinat synthase, a hot spot mutation in X-linked sideroblastic anaemia,
26 does not itself affect enzyme activity. *Eur J Haematol* 76(1):33-41.
- 27 Furuyama K, Sassa S. 2002. Multiple mechanisms for hereditary sideroblastic anemia. *Cell*
28 *Mol Biol (Noisy-le-grand)* 48(1):5-10.
- 29 Furuyama K, Uno R, Urabe A, Hayashi N, Fujita H, Kondo M, Sassa S, Yamamoto M. 1998.
30 R411C mutation of the ALAS2 gene encodes a pyridoxine-responsive enzyme with
31 low activity. *Br J Haematol* 103(3):839-41.
- 32 Gibson KD, Laver WG, Neuberger A. 1958. Initial stages in the biosynthesis of porphyrins. 2.
33 The formation of delta-aminolaevulic acid from glycine and succinyl-coenzyme A by
34 particles from chicken erythrocytes. *Biochem J* 70(1):71-81.
- 35 Goncalves P, Pereira JC, Ribeiro ML. 2004. Gene symbol: ALAS2. Disease: sideroblastic
36 anaemia. *Hum Genet* 115(6):532.
- 37 Grantham R. 1974. Amino acid difference formula to help explain protein evolution. *Science*
38 185(4154):862-4.
- 39 Guernsey DL, Jiang H, Campagna DR, Evans SC, Ferguson M, Kellogg MD, Lachance M,
40 Matsuoka M, Nightingale M, Rideout A and others. 2009. Mutations in mitochondrial
41 carrier family gene SLC25A38 cause nonsyndromic autosomal recessive congenital
42 sideroblastic anemia. *Nat Genet* 41(6):651-3.
- 43 Harigae H, Furuyama K. Hereditary sideroblastic anemia: pathophysiology and gene
44 mutations. *Int J Hematol* 92(3):425-31.
- 45 Harigae H, Furuyama K, Kimura A, Neriishi K, Tahara N, Kondo M, Hayashi N, Yamamoto
46 M, Sassa S, Sasaki T. 1999a. A novel mutation of the erythroid-specific delta-
47 aminolaevulinat synthase gene in a patient with X-linked sideroblastic anaemia. *Br J*
48 *Haematol* 106(1):175-7.
- 49 Harigae H, Furuyama K, Kudo K, Hayashi N, Yamamoto M, Sassa S, Sasaki T. 1999b. A
50 novel mutation of the erythroid-specific gamma-Aminolevulinat synthase gene in a
51
52
53
54
55
56
57
58
59
60

- 1
2 patient with non-inherited pyridoxine-responsive sideroblastic anemia. *Am J Hematol*
3 62(2):112-4.
- 4 Kannengiesser C, Brookes S, del Arroyo AG, Pham D, Bomblid J, Barrois M, Mauffret O,
5 Avril MF, Chompret A, Lenoir GM and others. 2009. Functional, structural, and
6 genetic evaluation of 20 CDKN2A germ line mutations identified in melanoma-prone
7 families or patients. *Hum Mutat* 30(4):564-74.
- 8 Lee PL, Barton JC, Rao SV, Acton RT, Adler BK, Beutler E. 2006. Three kinships with
9 ALAS2 P520L (c. 1559 C --> T) mutation, two in association with severe iron
10 overload, and one with sideroblastic anemia and severe iron overload. *Blood Cells*
11 *Mol Dis* 36(2):292-7.
- 12 Lien LF, Beattie DS. 1982. Comparisons and modifications of the colorimetric assay for
13 delta-aminolevulinic acid synthase. *Enzyme* 28(2-3):120-32.
- 14 Mauzerall D, Granick S. 1956. The occurrence and determination of delta-amino-levulinic
15 acid and porphobilinogen in urine. *J Biol Chem* 219(1):435-46.
- 16 May A, Bishop DF. 1998. The molecular biology and pyridoxine responsiveness of X-linked
17 sideroblastic anaemia. *Haematologica* 83(1):56-70.
- 18 May A, BC, Masters G., Kingston J., Lawless S., and Jenner M. . 2005. Severe Sideroblastic
19 Anaemia in an ALAS2 Compound Heterozygote for -206G, a Common Polymorphism,
20 and a Novel Mutation in Exon 11 (Lys535del) Linked to Lack of Haemoglobinisation
21 In Vitro and Ineffective Erythropoiesis In Vivo. *Blood (ASH Annual Meeting*
22 *Abstracts)* 106:3541.
- 23 Nakajima O, Takahashi S, Harigae H, Furuyama K, Hayashi N, Sassa S, Yamamoto M. 1999.
24 Heme deficiency in erythroid lineage causes differentiation arrest and cytoplasmic
25 iron overload. *EMBO J* 18(22):6282-9.
- 26 Ng PC, Henikoff S. 2003. SIFT: Predicting amino acid changes that affect protein function.
27 *Nucleic Acids Res* 31(13):3812-4.
- 28 Prades E, Chambon C, Dailey TA, Dailey HA, Briere J, Grandchamp B. 1995. A new
29 mutation of the ALAS2 gene in a large family with X-linked sideroblastic anemia.
30 *Hum Genet* 95(4):424-8.
- 31 Sayle RA, Milner-White EJ. 1995. RASMOL: biomolecular graphics for all. *Trends Biochem*
32 *Sci* 20(9):374.
- 33 Shemin D, Kikuchi G. 1958. Enzymatic synthesis of sigma-aminolevulinic acid. *Ann N Y*
34 *Acad Sci* 75(1):122-8.
- 35 Sunyaev S, Ramensky V, Koch I, Lathe W, 3rd, Kondrashov AS, Bork P. 2001. Prediction of
36 deleterious human alleles. *Hum Mol Genet* 10(6):591-7.
- 37 Surinya KH, Cox TC, May BK. 1997. Transcriptional regulation of the human erythroid 5-
38 aminolevulinic acid synthase gene. Identification of promoter elements and role of
39 regulatory proteins. *J Biol Chem* 272(42):26585-94.
- 40 Tavgigian SV, Deffenbaugh AM, Yin L, Judkins T, Scholl T, Samollow PB, de Silva D,
41 Zharkikh A, Thomas A. 2006. Comprehensive statistical study of 452 BRCA1
42 missense substitutions with classification of eight recurrent substitutions as neutral. *J*
43 *Med Genet* 43(4):295-305.
- 44 Yue P, Melamud E, Moulton J. 2006. SNPs3D: candidate gene and SNP selection for
45 association studies. *BMC Bioinformatics* 7:166.
- 46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 1: Hematological and biochemical parameters of patients presenting *ALAS2* mutations

Patient	Gender	Age at onset (years)	Pyridoxine Response	Hb (g/dL)	MCV (fL)	Tf Sat (%)	Ferritin (μg/L)	PP (μmoles/L RBC)	<i>ALAS2</i> Mutation ^a			Genetic report
									localization	cDNA ^b	Protein	
1	F	43	-	11.2	96	100	371	n.a.	exon 5	c.509G>A	p.Arg170His	(May and Bishop, 1998)
2	F	0.5	-	8	84	100	1448	n.a.	exon 6	c.653G>A	p.Arg218His	present study
3	M	0.5	+	1.5	69	n.a.	256	n.a.	exon 6	c.724G>A	p.Glu242Lys	present study
4	F	20	+	9.2	41 ^c	68	899	n.a.	exon 6	c.787G>A	p.Asp263Asn	(Bottomley, 2004)
5	M	31	+	3.5	76	n.a.	1172	1.40	exon 8	c.1016C>T	p.Pro339Leu	present study
6	M	47	n.a.	6.3	<70	63	2537	1.70	exon 8	c.1123C>T	p.Arg375Cys	present study
7	M	7	+	7.2	60	86	780	n.a.	exon 9	c.1231C>T	p.Arg411Cys	(Bottomley, 2004) ^e
8	F ^d	n.a.	n.a.	9.1	41 ^c	71	600	1.80	exon 9	c.1232G>A	p.Arg411His	(Goncalves, et al., 2004)
9	F	63	+	10.4	73	70	428	1.65	exon 9	c.1232G>A	p.Arg411His	(Goncalves, et al., 2004)
10	M	38	+	10.4	70	93	2284	n.a.	exon 9	c.1354C>G	p.Arg452Gly	present study
11	M	20	+	11.3	62	100	1172	n.a.	exon 9	c.1354C>T	p.Arg452Cys	(Bottomley, et al., 1995) ^f
12	M	n.a.	+	10	<70	n.a.	1000	0.56	exon 9	c.1354C>T	p.Arg452Cys	(Bottomley, et al., 1995) ^f
13	F	45	-	8.5	56	n.a.	n.a.	n.a.	exon 9	c.1559C>T	p.Pro520Leu	(Lee, et al., 2006)
14	M	46	-	13.2	68	63	1000	0.64	exon 11	c.1715G>A	p.Arg572His	present study
15	M	57	+	12.2	73	28	1000	n.a.	exon 11	c.1715G>A	p.Arg572His	present study
16	M	0.75	+/-	6.3	53	n.a.	1200	n.a.	Promoter	c.-91_-44 del	-	present study

Formatted: Highlight

1
2 M: Male, F: Female, Hb: Hemoglobin; MCV: Mean Corpuscular Volume; Tf Sat: Transferrin Saturation; PP: erythrocyte protoporphyrin; RBC:
3 red blood cells; n.a.: not available.

4 ^a the *Genbank reference sequence for ALAS2* gene are: Genbank genomic: NG_008983.1, Genbank mRNA: NM_000032.4 and Genbank protein:
5 NP_000023.2.

6 ^b Nucleotide numbering reflects cDNA numbering with +1 corresponding to the A of the ATG translation initiation codon in the reference
7 sequence, according to HGVS guidelines (www.hgvs.org/mutnomen). The initiation codon is codon 1.

8 ^c: values of MCV were indicated for the microcytic population of RBCs in female patients in whom two populations of RBCs were detected.

9 ^d not informative for X inactivation.

10 Expression data have been studied for the following mutations: ^e pR411C (Furuyama, et al., 1998), and ^f p.R452C (Furuyama, et al., 2006).

11 Normal values: Hb: 12-15.5 g/dL (anemia: Females <12g/dL, Males <13g/dL), MCV: 80-90 fL (microcytosis: <80fL), Tr Sat: 12-45% (Females)
12 15-50% (Males), Serum Ferritin: Females 20-150 µg/L, Males 30-300 µg/L. PP <1.9µmoles/L RBC.
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

TABLE 2: Summary of results for missense mutations

ALAS2 Mutation	Structural impact ^a		<i>In silico</i> protein score	ALAS2 activity	
	AA RC	Localization		Standard: with added PLP	Specific: without added PLP ^b
p.Arg170His ^c	Arg28	Internal β1-sheet strand 1	Deleterious	117 %	Defective
p.Arg218His	Ala75	Internal α3-helix	Neutral	83 %	Defective
p.Glu242Lys	Glu99	Surface α4-helix	Neutral	17 % ‡	ND
p.Asp263Asn	Asp120	Internal α5-helix	Deleterious	14 % ‡	ND
p.Pro339Leu	Pro196	Surface 1aa before α8-helix	Deleterious	65 % ‡	ND

p.Arg375Cys	Arg232	Surface α 8-helix	Deleterious	53 % \ddagger	ND
p.Arg411His	Arg268	Internal α 1-helix	Deleterious	23 % \ddagger	ND
p.Arg411Cys	Arg268		Deleterious	25 % ^f	ND
p.Arg452Gly ^d	Met309	Surface α 14-helix	Deleterious	109 %	Normal
p.Arg452Cys ^d	Met309		Deleterious	100 % ^f	ND
p.Pro520Leu	Pro377	Internal	Deleterious	87%	ND
p.Arg572His	ND ^e	ND ^e	Deleterious	126 %	Normal

AA RC: amino acid, *Rhodobacter capsulatus*; ND: not determined; \ddagger Student's t-test, p value < 0.05

^a crystallography of ALAS2 from *R. capsulatus* permitted molecular modeling to predict the localizations of numerous mutations on the protein (Rasmol, PDP 2BWN, 2BWO and 2BW).

^b or preincubated at 37°C.

^{c d}: These amino acids are hot spots of mutation with numerous substitutions: R170L/S/C (Edgar, et al., 1998; Furuyama and Sassa, 2002; May and Bishop, 1998) and R452H/C/S/G (Bottomley, et al., 1995) and this study.

^e Structural prediction for R572H is not possible because the C-terminal part of human enzyme is longer than enzyme of *R. capsulatus*.

^f previously described (Furuyama, et al., 2006).

Figure Legends

Figure 1: Hemizygous deletion of 48 base pairs in the proximal promoter of *ALAS2* gene

A: PCR amplification of the promoter region from a normal control (lane 1; expected size 627 bp); male proband 15 (lane 2; shorter PCR product of 579 bp) and his mother (lane 3; healthy carrier); M: DNA molecular weight markers (Fermentas, 100 bp ladder);

B: Sequence of the proximal promoter of the *ALAS2* gene (Adapted from Cox, et al., 1991) showing the TATA-like box (in bold), the beginning of exon 1 (underlined), and the deletion (underlined in gray)

Figure 2: Residual activities of the various different recombinant *ALAS2* mutant enzymes assayed under standard conditions

The residual activity of each mutant is expressed as a percentage of the normal enzyme activity as described in Material and Methods. Enzyme activity was measured on at least 3 independent bacterial cultures. The statistical significance of comparisons of the specific activities between each mutant and the normal enzyme was established using Student's t-test (*: p value < 0.05). Five mutants (E242K, D263N P339L, R375C and R411H) display significant loss-of-function.

Figure 3: PLP-dependence and thermosensitivity of the recombinant normal and mutant *ALAS2*

A/ The specific activity of wild type enzyme and four mutant enzymes (R170H, R218H, R452G and R572H, showing no loss-of-function under standard conditions) was measured without adding PLP to the assay, as described in Material and Methods. Specific activities are expressed in pmoles of ALA produced by mg protein after subtracting the specific activity of C344X (negative control). The statistical significance of the comparisons between each

1
2 mutant and the normal enzyme was established using Student-s t-test (*: p value < 0.05). Two
3
4 mutants (R170H and R218H) display PLP sensitivity.

5
6 B/ The specific activity of wild type enzyme and four mutant enzymes (R170H, R218H,
7
8 R452G and R572H) was measured after preincubating for 30 or 60 minutes before the assay,
9
10 as described in Material and Methods. The statistical significance of comparisons between
11
12 each mutant and the normal enzyme was established using Student's t-test (*: p value < 0.05).

13
14 Two mutants (R170H and R218H) are thermosensitive.
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Peer Review

Table 1: Hematological and biochemical parameters of patients presenting *ALAS2* mutations

Patient	Gender	Age at onset (years)	Pyridoxine Response	Hb (g/dL)	MCV (fL)	Tf Sat (%)	Ferritin (μg/L)	PP (μmoles/L RBC)	<i>ALAS2</i> Mutation ^a			Genetic report
									localization	cDNA ^b	Protein	
1	F	43	-	11.2	96	100	371	n.a.	exon 5	c.509G>A	p.Arg170His	(May and Bishop, 1998)
2	F	0.5	-	8	84	100	1448	n.a.	exon 6	c.653G>A	p.Arg218His	present study
3	M	0.5	+	1.5	69	n.a.	256	n.a.	exon 6	c.724G>A	p.Glu242Lys	present study
4	F	20	+	9.2	41 ^c	68	899	n.a.	exon 6	c.787G>A	p.Asp263Asn	(Bottomley, 2004)
5	M	31	+	3.5	76	n.a.	1172	1.40	exon 8	c.1016C>T	p.Pro339Leu	present study
6	M	47	n.a.	6.3	<70	63	2537	1.70	exon 8	c.1123C>T	p.Arg375Cys	present study
7	M	7	+	7.2	60	86	780	n.a.	exon 9	c.1231C>T	p.Arg411Cys	(Bottomley, 2004) ^e
8	F ^d	n.a.	n.a.	9.1	41 ^c	71	600	1.80	exon 9	c.1232G>A	p.Arg411His	(Goncalves, et al., 2004)
9	F	63	+	10.4	73	70	428	1.65	exon 9	c.1232G>A	p.Arg411His	(Goncalves, et al., 2004)
10	M	38	+	10.4	70	93	2284	n.a.	exon 9	c.1354C>G	p.Arg452Gly	present study
11	M	20	+	11.3	62	100	1172	n.a.	exon 9	c.1354C>T	p.Arg452Cys	(Bottomley, et al., 1995) ^f
12	M	n.a.	+	10	<70	n.a.	1000	0.56	exon 9	c.1354C>T	p.Arg452Cys	(Bottomley, et al., 1995) ^f
13	F	45	-	8.5	56	n.a.	n.a.	n.a.	exon 9	c.1559C>T	p.Pro520Leu	(Lee, et al., 2006)
14	M	46	-	13.2	68	63	1000	0.64	exon 11	c.1715G>A	p.Arg572His	present study
15	M	57	+	12.2	73	28	1000	n.a.	exon 11	c.1715G>A	p.Arg572His	present study
16	M	0.75	+/-	6.3	53	n.a.	1200	n.a.	Promoter	c.-91_-44 del	-	present study

1
2
3 M: Male, F: Female, Hb: Hemoglobin; MCV: Mean Corpuscular Volume; Tf Sat: Transferrin Saturation; PP: erythrocyte protoporphyrin; RBC:
4 red blood cells; n.a.: not available.

5 ^a the *Genbank reference sequence for ALAS2* gene are: Genbank genomic: NG_008983.1, Genbank mRNA: NM_000032.4 and Genbank protein:
6 NP_000023.2.

7 ^b Nucleotide numbering reflects cDNA numbering with +1 corresponding to the A of the ATG translation initiation codon in the reference
8 sequence, according to HGVS guidelines (www.hgvs.org/mutnomen). The initiation codon is codon 1.

9 ^c: values of MCV were indicated for the microcytic population of RBCs in female patients in whom two populations of RBCs were detected.

10 ^d not informative for X inactivation.

11 Expression data have been studied for the following mutations: ^e pR411C (Furuyama, et al., 1998), and ^f p.R452C (Furuyama, et al., 2006).

12 Normal values: Hb: 12-15.5 g/dL (anemia: Females <12g/dL, Males <13g/dL), MCV: 80-90 fL (microcytosis: <80fL), Tr Sat: 12-45% (Females)
13 15-50% (Males), Serum Ferritin: Females 20-150 µg/L, Males 30-300 µg/L. PP <1.9µmoles/L RBC.
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

TABLE 2: Summary of results for missense mutations

ALAS2 Mutation	Structural impact ^a		<i>In silico</i> protein score	ALAS2 activity	
	AA RC	Localization		Standard: with added PLP	Specific: without added PLP ^b
p.Arg170His ^c	Arg28	Internal β1-sheet strand 1	Deleterious	117 %	Defective
p.Arg218His	Ala75	Internal α3-helix	Neutral	83 %	Defective
p.Glu242Lys	Glu99	Surface α4-helix	Neutral	17 % ‡	ND
p.Asp263Asn	Asp120	Internal α5-helix	Deleterious	14 % ‡	ND
p.Pro339Leu	Pro196	Surface 1aa before α8-helix	Deleterious	65 % ‡	ND

p.Arg375Cys	Arg232	Surface α8-helix	Deleterious	53 % ‡	ND
p.Arg411His	Arg268	Internal α1-helix	Deleterious	23 % ‡	ND
p.Arg411Cys	Arg268		Deleterious	25 % ^f	ND
p.Arg452Gly ^d	Met309	Surface α14-helix	Deleterious	109 %	Normal
p.Arg452Cys ^d	Met309		Deleterious	100 % ^f	ND
p.Pro520Leu	Pro377	Internal	Deleterious	87%	ND
p.Arg572His	ND ^e	ND ^e	Deleterious	126 %	Normal

AA RC: amino acid, *Rhodobacter capsulatus*; ND: not determined; ‡ Student's t-test, p value < 0.05

^a crystallography of ALAS2 from *R. capsulatus* permitted molecular modeling to predict the localizations of numerous mutations on the protein (Rasmol, PDP 2BWN, 2BWO and 2BW).

^b or preincubated at 37°C.

^{c d} : These amino acids are hot spots of mutation with numerous substitutions: R170L/S/C (Edgar, et al., 1998; Furuyama and Sassa, 2002; May and Bishop, 1998) and R452H/C/S/G (Bottomley, et al., 1995) and this study.

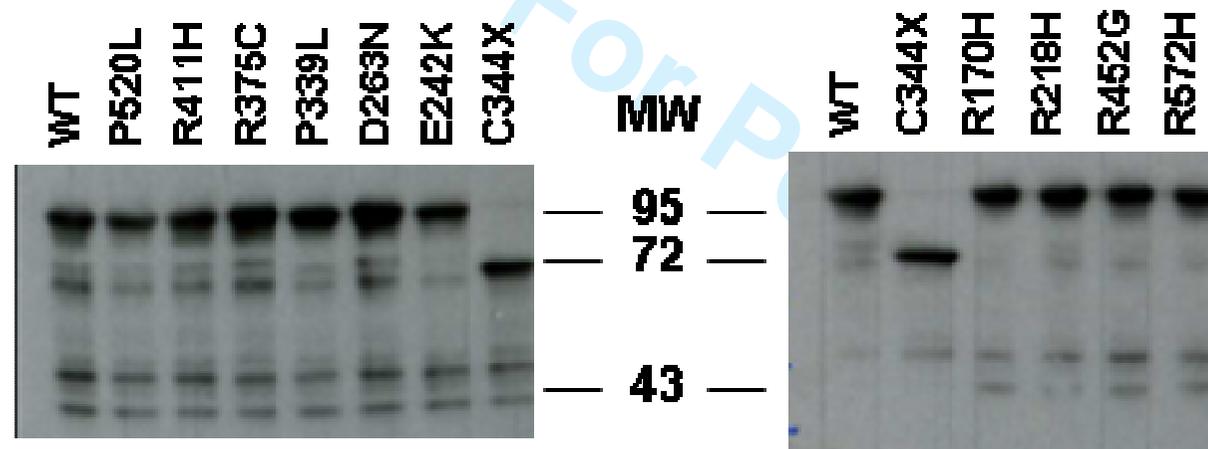
^e Structural prediction for R572H is not possible because the C-terminal part of human enzyme is longer than enzyme of *R. capsulatus*.

^f previously described (Furuyama, et al., 2006)

Supp. figure S1: Immunoblotting

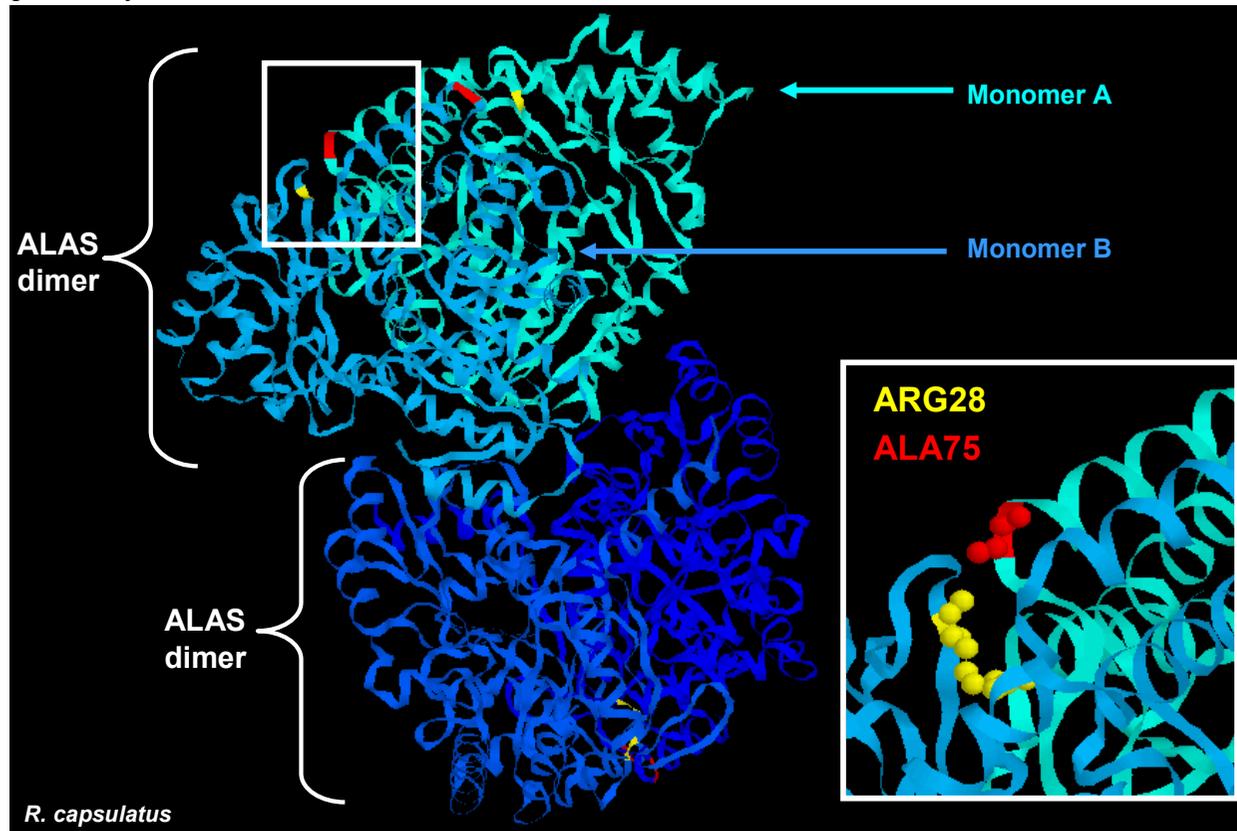
Western blot analysis of bacterial cell lysates from *E. coli* transformed with normal and mutant ALAS2 cDNAs. After the transfer, the membranes were probed with a primary antibody directed against MBP.

MW: reported molecular weight of the ladder (PageRuler™ prestained protein ladder, Fermentas, Thermo Fischer Scientific).



Suppl. figure S2: Localization of Arg28 (e.g. R170 in human) and Ala75 (e.g. R218 in human) on ALAS of *Rhodobacter capsulatus*.

The structure of ALAS of *R. capsulatus* (PDB 2BWO, Rasmol software, 2 ALAS dimers) is represented. The blue ribbon and the cyan ribbon correspond to two monomers. Arg28 (in yellow) on one monomer and Ala75 (in red) on the other monomer are quite close to each other in the quaternary structure.



Supp. table S1: Primers Table

Exon		Sequence	Amplicon length (bp)
Prom -1	F R	TGG TCT GAT TCC AAA GCC CAA ATG CGA GGA AAG AGA CAA AAA GGG GGA G	627
2	F R	TTG CCA GGC CCT CAT GAT GGA A AGG CAA AGA TGG CCA GTA TAA CTT GGA	325
3	F R	GGC TTT AGG GGT ACA TTA GAT CTC AGC A ATC ATG GGA TGT GTA CTG GCT GCT TTT	324
4	F R	TGT GTT GCA TTG AGC TTA AAG AGG ACA A AAG GCC CTT CTG TAC TGT TTC CCC TAC T	295
5	F R	GAG TTG GAG AAC TCA AAA TCA GCA ACA T CCC AAG TTT CCA CTG CCA GCT CT	418
	R	Internal sequence Primer TTC CAT GTG TGG TTT TTC ATC TCC TCT	380
6	F R	GAG AAA CCT ACC CAG TTC CTC GAT GC ACT GGA TGC TGT ATT GCA GGA TAC CA	316
7	F R	GGT TGA AGT GGG AGT ACT GGG ACA GA TGA TCA TCA TGG TTT TTG TGA GAC CAA	296
8	F R	GAG ATG GAG CTG GGG AAG GGT TAT ATT TTG TAA GGG CCT CCT CTC TGG A	280
9	F R	TGT TGC TCT GGG ACT GAT TAT GGG A GGA GCG TGA GGC TCC CAG AAT AA	387
10	F R	AGC TAG TGA TGG TGG AGC CAG AGT G TCT TTC AGA TCC TGG GGC TGA GG	282
11	F R	GGC TCA TCT GTA CTG TGA CAG ATT TGG A GGC ACA CAA CAA AGC AGA AGA CAG G	324

Supp. Table S2: *in silico* evaluations of 12 *ALAS2* mutations

ALAS2 Mutation (protein)	Grantham Score	GVDG [‡]	PANTHER	SIFT	Polyphen	UMD predictor	SNP3D	<i>In silico</i> Score [§]
p.Arg170His	29	Moderate risk C25	Highly deleterious -4.1649	Affected 0.00	probably damaging PSIC: 2.626	Probable polymorphism 59	Deleterious -1.29	Deleterious 5/7
p.Arg218His	29	Weak risk C0	Unlikely deleterious -2.31925	Tolerated 0.11	Benign PSIC: 0.241	Polymorphism 47	Non deleterious 1.44	Neutral 0/7
p.Glu242Lys	56	High risk C55	Unlikely deleterious -1.99823	Tolerated 0.44	Benign PSIC: 1.163	Polymorphism 41	Non deleterious 1.41	Neutral 1/7
p.Asp263Asn	23	Weak risk C15	Probably deleterious -2.78604	Affected 0.00	possibly damaging PSIC: 1.976	Probable polymorphism 53	Deleterious -0.60	Deleterious 4/7
p.Pro339Leu	98	High risk C65	Highly deleterious -4.73676	Affected 0.00	probably damaging PSIC: 3.181	Pathogenic 82	Deleterious -2.34	Deleterious 6/7
p.Arg375Cys	180	High risk C65	Highly deleterious -4.79784	Affected 0.00	probably damaging PSIC: 2.734	Pathogenic 100	Deleterious -1.12	Deleterious 7/7
p.Arg411His	29	Moderate risk C25	<i>error</i> *	Affected 0.00	probably damaging PSIC: 2.686	Pathogenic 100	Deleterious -2.63	Deleterious 5/6
p.Arg411Cys	180	High risk C65	<i>error</i> *	Affected 0.00	probably damaging PSIC: 3.361	Probably pathogenic 71	Deleterious -3.31	Deleterious 6/6

p.Arg452Gly	125	High risk C65	Possibly deleterious -2.75867	Tolerated 0.024	probably damaging PSIC: 2.119	pathogenic 82	Non Deleterious 1.16	Deleterious 6/7
p.Arg452Cys	180	High risk C65	Highly deleterious -4.26738	Affected 0.03	probably damaging PSIC: 2.174	Pathogenic 100	Non Deleterious 0.47	Deleterious 6/7
p.Pro520Leu	98	High risk C65	Highly deleterious -4.7838	Affected 0.01	probably damaging PSIC: 2.899	Pathogenic 82	Non Deleterious 0.46	Deleterious 5/7
p.Arg572His	29	Weak risk C0	Unlikely deleterious -2.25602	Affected 0.01	probably damaging PSIC: 2.103	Pathogenic 76	<i>error</i>	Deleterious 3/6

* failure of the software to give a prediction

£ For GVGD we used the ALAS2 sequences for *Homo sapiens* (isoform 1), *Mus musculus*, *Rattus norvegicus*, *Bos taurus* and *Danio rerio*.

\$ To get an overall impression of the likely impact of each mutation, we calculated a “prediction score” from the number of programs that predicted that the alteration would be deleterious (Grantham score >100; GVGD: C25-C65; PANTHER: highly/probably deleterious; SIFT: affected; polyphen: damaging; UMD predictor: pathogenous; SNP3D: deleterious).

Supp. table S3: Proposed grouping of Congenital Sideroblastic Anemia patients

Congenital Sideroblastic Anemia form (Gene)	No. of mutations	No. of probands	Females / Males	Range of ages at diagnosis §	Characteristics of anemia (MCV)	Severity of Anemia ‡ (Lowest Hb)
X-linked sideroblastic anemia (<i>ALAS2</i>)	13	16	6/10	6m-63y	Microcytic in most cases	Mild to severe
Autosomal recessive (<i>SLC25A38</i>)	4	4	2/2	2d-3y	microcytic	Severe
Unexplained CSA	-	2	0/2	3m-7m	Microcytic	Severe
	-	6	4/2	early-62y	Non microcytic	Mild (2) Severe (3) NA (1)
	-	1*	0/1	NA	NA	NA

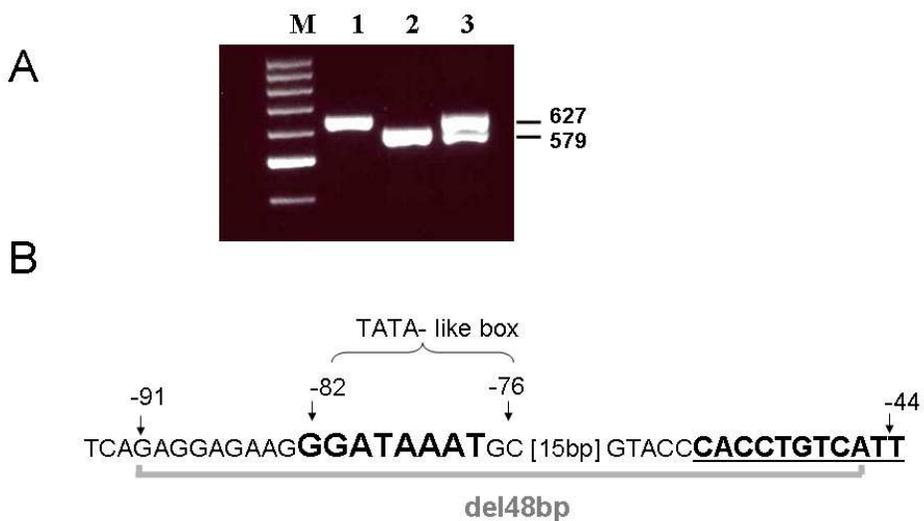
§ d: day; m: month; y: years

‡ Classification of anemia: Mild, Hb >10 g/dl; moderate, Hb 7–10 g/dl; severe Hb <7 g/dl; NA: not available

* Familial case (another brother affected)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 1

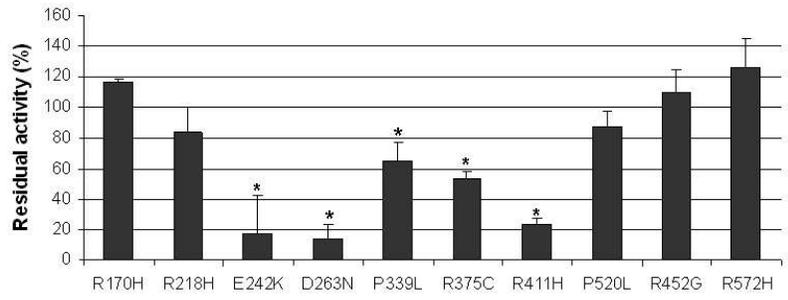


254x190mm (96 x 96 DPI)

Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

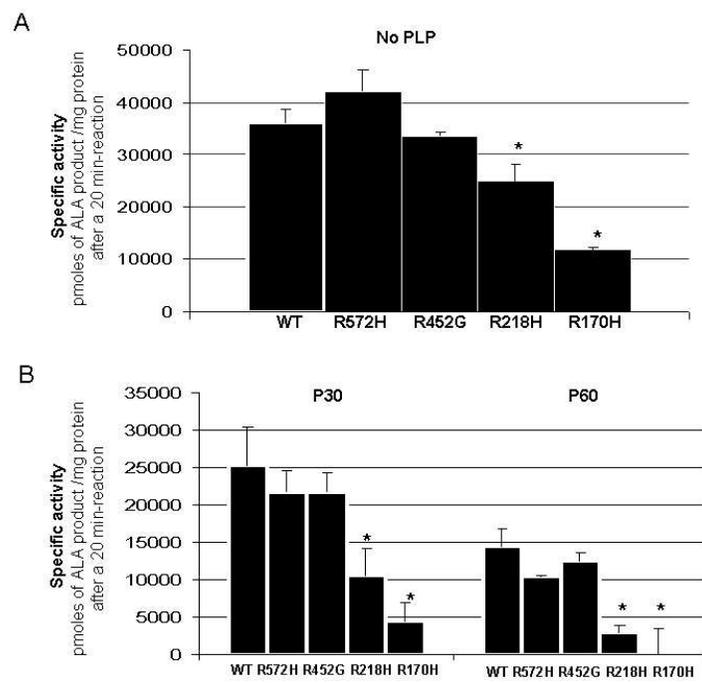
Figure 2



254x190mm (96 x 96 DPI)

Review

Figure 3



254x190mm (96 x 96 DPI)