Hematologic abnormalities in Shwachman Diamond syndrome: lack of genotype-phenotype relationship

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Hematologic abnormalities in Shwachman Diamond syndrome: lack of genotype-phenotype relationship

Taco W. Kuipers, Mariel Alders, Anton T. J. Tool, Clemens Mellink, Dirk Roos, and Raoul C. M. Hennekam

Shwachman-Diamond syndrome (SDS) is an autosomal-recessive disorder characterized by short stature, exocrine pancreatic insufficiency, and hematologic defects. The causative SBDS gene was sequenced in 20 of 23 unrelated patients with clinical SDS. Mutations in the SBDS gene were found in 75%, being identical in 11 patients. Hematologic parameters for all 3 lineages were determined over time such as absolute neutrophil counts (ANCs), granulocyte functions, and erythroid and myeloid colony formation (erythroid burst-forming unit [BFU-E] and granulocyte-monocyte colony-forming unit [CFU-GM]) from hematopoietic progenitor cells, percentage of fetal hemoglobin (HbF), and platelet counts. Persistent neutropenia was present in 43% in the absence of apoptosis and unrelated to chemotaxis defects (in 65%) or infection rate. Irrespective of the ANC in vivo, abnormal CFU-GM was observed in all patients with SDS tested (14 of 14), whereas BFU-E was less often affected (9 of 14). Cytogenetic aberrations occurred in 5 of 19 patients in the absence of myelodysplasia. One child died during allogeneic bone marrow transplantation. In conclusion, neutropenia and defective chemotaxis did not result in severe clinical infection in SDS. CFU-GMs were impaired in all patients tested. From the SBDS sequence data, we conclude that in patients with genetically proven SDS a genotype-phenotype relationship in SDS does not exist in clinical and hematologic terms. (Blood. 2005;106:356-361)

Introduction

Shwachman-Diamond syndrome (SDS; OMIM 260400) is an autosomal, recessively-inherited disorder showing a wide variety of abnormalities and symptoms. It is mainly characterized by short stature, exocrine pancreatic insufficiency, and bone marrow dysfunction. Several studies have shown that, with advancing age, 40% to 60% of patients become pancreatic sufficient. Elevated liver enzymes and hepatomegaly have been observed in the first years of life with subsequent improvement over the years.

Intermittent neutropenia is the most common hematologic finding in SDS. Hematologic manifestations other than neutropenia include anemia, raised fetal hemoglobin (HbF) levels, thrombocytopenia, and, finally, aplastic anemia. Granulocyte colony-stimulating factor (G-CSF) has been used in some SDS subjects with severe neutropenia but is not generally advised because of the potential risk of acute myeloid leukemia.

Growth retardation is the third typical manifestation: weight and length are already deficient at birth and remain decreased over time. A broad spectrum of skeletal abnormalities has been observed, of which metaphyseal dysplasia of ribs and long bones is the most common symptom. Several additional, less frequently observed clinical features such as heart failure or psychomotor retardation have been described.

Although the genetic basis of this rare disease has recently been described, no unifying pathogenic mechanism(s) has yet been shown to be responsible for SDS. Indirect lines of evidence from orthologs such as YLR022c, indicate that the SBDS gene may encode an RNA-processing enzyme. Seventy-five percent of the alleles in SDS were the result of a gene conversion confined to a short segment of about 240 base pairs (derived from an inactive pseudogene). Of the affected individuals, about 90% carry 1 and 60% carry 2 converted alleles. Alleles from affected individuals without conversion mutations had other changes in the coding region of SBDS that led to frameshift and missense changes.

Neutrophils are produced in large numbers every day in the bone marrow, being predisposed to demise by apoptosis, a process that prevents the cytotoxic contents from the neutrophil granules to be released into the surrounding tissues and facilitates the harmless elimination of these cells by tissue macrophages. Aging of normal neutrophils is accompanied by a progressive loss of functions, such as adherence, chemotaxis, and respiratory burst. We have studied the functional characteristics of neutrophils in other syndromes with concomitant neutropenia, and others have reported that in glycogen storage disease type 1-b (GSD1b) the functional defects of circulating neutrophils were largely due to premature apoptosis. In SDS, apoptosis has been noticed before in cultures of hematopoietic stem cells. However, apoptosis may be eminent at early stages only, whereas the mature circulating neutrophils are not affected and still functional.

To investigate the functional characteristics of neutrophils in SDS more closely, we sequenced the SBDS gene in a group of patients clinically diagnosed with SDS. We investigated long-term hematologic parameters, colony-forming potential of committed PHAGOCYTES
<table>
<thead>
<tr>
<th>Patient (sex)</th>
<th>Age, y</th>
<th>SBDS mutation</th>
<th>Skin lesions</th>
<th>Hepatitis</th>
<th>Gastrointestinal symptoms</th>
<th>BFU-E‡</th>
<th>CFU-GM‡</th>
<th>Cytogenetics§</th>
<th>Hb, g/dL, and HbF (%)</th>
<th>Platelets, 10⁹/L</th>
<th>ANC, μL</th>
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(continued)
**Table 1. Patient characteristics**

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<td>34</td>
<td>25</td>
<td>16 (F)</td>
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</table>

M indicates male; F, female.

Elastase is expressed as g/kg.

†Infections are defined as follows: +, only at early age; +, invasive or recurrent that required antibiotics.

‡Normal BFU-E values are 295, 100.8 colonies/105 nuclear cells (nucleated BM cells), CFU-GM values are 492, 120.2 colonies/105 nuclear cells (nucleated BM cells), age-matched.

ANC indicates absolute neutrophil counts (low, normal, >70% of the mean of the day as well as abnormal; blanks without stimuli were not subtracted (see Figure IA).

Neutrophil purification and functional testing

Heparinized venous blood was collected from healthy donors and from patients with SDS, after obtaining informed consent. Granulocytes were isolated as described. Purity was always greater than 95%. In some experiments whole leukocyte preparations were used from which the erythrocytes were lysed by ice-cold isotonic NH4Cl solution.

**Patients, materials, and methods**

**SDS patient definition and inclusion**

Patients were defined by the following major criteria: (1) early gastrointestinal symptoms (fat malabsorption and/or unexplained decrease in serum levels of fat-soluble vitamins, low fecal levels of elastase and/or chymotrypsin in the presence of normal sweat tests to exclude cystic fibrosis), (2) hematologic findings (unexplained anemia, low neutrophil and/or platelet number), (3) radiologic findings compatible with Shwachman-Diamond syndrome, and (4) growth failure. For a diagnosis of SDS, evidence of pancreatic exocrine dysfunction is obligatory at an early age. The presence of 2 major criteria made the diagnosis probable, and of 3 criteria definite, irrespective of the genetic analysis of the SBDS gene. Minor features were scored but not considered for the diagnosis. These features consisted of an unexplained hepatitis and/or hepatomegaly, skin manifestations, psychomotor skills, and behavioral difficulties. The study was approved by the institutional medical ethical committee of the AMC in accordance with the standards laid down in the 1964 declaration of Helsinki.

**Molecular studies**

Genomic DNA from peripheral mononuclear cells and fibroblasts from the patients were extracted by standard methods. All coding exons of the SBDS gene were amplified in separate polymerase chain reactions (PCRs). Sequencing was performed with the phycocerythrin (PE) dye terminator kit, and products were analyzed on an automated sequencer (ABI3100; Applied Biosystems, Foster City, CA). The genomic DNA was tested after written consent was obtained from the parent(s) and the patient (when older than 12 years of age). There were 3 refusals.

**Hematologic studies**

Morphologic analysis demonstrated hypocellular BM in smears, in some patients confirmed by BM biopsies. No excess of collagen or signs of fibrosis, disturbed bone marrow stroma development, or disorganized hematopoiesis was observed. Absolute numbers of progenitor B cells (CD19+, CD10-, CD24+), T cells (CD2+, CD3-, CD4+, CD8-), natural killer (NK) cells (CD3+, CD16+, CD56+), and myeloid cells (CD15-, CD14-, CD16-, CD65+) were determined by standard fluorescence-activated cell scan (FACSscan) procedures. Colony-forming units of the erythroid and granulocyte-macrophage progenitors (erythroid burst-forming unit [BFU-E] and granulocyte-monocyte colony-forming unit [CFU-GM]) were determined in a 10- to 14-day semisolid culture and compared with normal age-matched values.

**Cytogenetic analysis**

Freshly obtained bone marrow samples were collected, cultured (without stimulation) in RPMI-1640 supplemented with 15% fetal calf serum for 24 hours, and harvested according to standard protocols. Phthohemagglutinin (PHA)—stimulated peripheral blood lymphocytes were cultured for 72 hours. Metaphase chromosomes were analyzed with a routine Q-banding method (QFA), and abnormal clones were defined according to the International System for Human Cytogenetic Nomenclature.

**Neutrophil purification and functional testing**

Granulocytes were isolated from healthy donors and from patients with SDS, after obtaining informed consent. Granulocytes were isolated as described. Purity was always greater than 95%. In some experiments whole leukocyte preparations were used from which the erythrocytes were lysed by ice-cold isotonic NH4Cl solution.
Neutrophil migration was assessed by means of the Fluoroblok inserts (Falcon; Becton Dickinson, San Jose, CA). Cells (5 × 10⁶/mL) were labeled with calcine-AM (1 μM final concentration; Molecular Probes, Leiden, Netherlands) for 30 minutes at 37°C, washed twice, and resuspended in HEPES (N-2-hydroxyethylpiperazine-N’-2-ethanesulfonic acid) buffer at a concentration of 2 × 10⁶/mL. Chemotactant solution (platelet activating factor [PAF], interleukin 8 [IL-8], and complement 5α [C5α], all at 10 nM) or medium alone (0.8 mL/well) were placed in a 24-well plate, and 0.3 mL cell suspension was delivered to the inserts (3-μm pore size) and placed in the 24-well plate. Cell migration was assessed by measuring fluorescence in the lower compartment at 2.5-minute intervals for 45 minutes with the HTS7000+ plate reader (Perkin Elmer, Norwalk, CT). Maximal slope of migration was estimated over a 10-minute interval.

Nicotinamide adenine dinucleotide phosphate (NADPH)-oxidase activity was assessed as hydrogen peroxide production determined by an Amplex Red kit (Molecular Probes). Neutrophils (1 × 10⁶/mL) were stimulated with 1 ng/mL serum-treated zymosan (STZ), or 100 ng/mL phorbol 12-myristate 13-acetate (PMA), in the presence of Amplex Red (0.5 μM) and horseradish peroxidase (1 U/mL). Fluorescence was measured at 30-second intervals for 20 minutes with the HTS7000+ plate reader. Maximal slope of H₂O₂ release was assessed over a 2-minute interval.

Annexin-V binding, mitochondrial staining, and morphology were performed exactly as described. Morphology was determined after Giemsa staining of cytoSpin preparations. Apoptotic morphology was defined as the presence of condensed nuclei and simultaneous loss of the polygonal segmental nuclear appearance.

**Statistics**

Statistical analysis was performed with the SPSS package for Windows, version 10.0 (SPSS, Chicago, IL). For normally distributed data the Student t test was used to compare group means, otherwise the Mann-Whitney U test was applied. A 2-sided P value of less than .05 was considered statistically significant.

**Results and discussion**

The **SDS** gene was sequenced in all but 3 cases clinically diagnosed as SDS. These latter 3 patients had gastrointestinal features as well as hematologic findings compatible with SDS (Table 1). Other causes had been excluded. In the other 20 patients, genetic abnormalities were found in the majority of patients. There were only a limited number of mutations present in our cohort. One mutation had not been reported until recently in Japanese patients (Table 1). The lack of abnormalities in some of the patients may be related to the age of radiologic scoring. Some had a mild anemia most often normocytic without iron deficiency, with normal serum ferritin and iron-binding capacity. There had been no transfusions. Two patients had a mild increase in HbF compared with age control subjects. Some patients had a borderline increase in HbF%. We classified the patients into 3 groups according to their ANC (serious neutropenia with < 600 polymorphonuclear neutrophils [PMNs]/μL, moderate neutropenia with 600-1200 PMNs/μL, and no relevant neutropenia with > 1200 PMNs/μL). Neutrophil counts were normal in 5 patients and moderately affected in 8 patients. Some of the patients became seriously neutropenic during infections only. Neutropenia and circulating myeloid progenitor cells disappeared spontaneously at the time the infection resolved (patients 8, 14, 15). In 10 patients a severe chronic neutropenia for more than 6 months was present (patients 1, 4, 5, 7, 13, 16, 18, 20, 21, 22). One patient was put on G-CSF (patient 7; up to 30 μg/kg, 3 times a week) because of repeated infections (patients 1, 4, 5, 7, 13, 16, 18, 20, 21, 22). One patient was put on G-CSF (patient 7; up to 30 μg/kg, 3 times a week) because of repeated infections resulting from congenital aplastic anemia. The patient’s response to G-CSF did not result in a significant rise in circulating neutrophil numbers, although her clinical condition improved considerably. Apart from this single case, we may conclude that the rate of infection was not strongly increased in our cohort.

We tested both neutrophil numbers and functions in 20 patients with SDS (Table 1). Directed cell motility (chemotaxis) of neutrophils can be disturbed in SDS. We classified the patients into 3 groups according to their ANC (serious neutropenia with < 600 polymorphonuclear neutrophils [PMNs]/μL, moderate neutropenia with 600-1200 PMNs/μL, and no relevant neutropenia with > 1200 PMNs/μL). Neutrophil counts were normal in 5 patients and moderately affected in 8 patients. Some of the patients became seriously neutropenic during infections only. Neutropenia and circulating myeloid progenitor cells disappeared spontaneously at the time the infection resolved (patients 8, 14, 15). In 10 patients a severe chronic neutropenia for more than 6 months was present (patients 1, 4, 5, 7, 13, 16, 18, 20, 21, 22). One patient was put on G-CSF (patient 7; up to 30 μg/kg, 3 times a week) because of repeated infections resulting from congenital aplastic anemia. The patient’s response to G-CSF did not result in a significant rise in circulating neutrophil numbers, although her clinical condition improved considerably. Apart from this single case, we may conclude that the rate of infection was not strongly increased in our cohort.

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with all 3 stimuli used from the controls of that day (taking 70% as cut-off as in Table 1). In a dose-response study over a log range in 3 of the patients with SDS with an abnormal chemotaxis response we found similar bell-shaped curves as well as the same optimal concentration for the induction of motility in the patients' neutrophils compared with control cells (data not shown). Chemotaxis defects did not correlate with ANC scores (Table 1; P = .8), which may indicate that there is no altered motility because of the presence of younger and more immature neutrophils in these patients.

The reason for the neutropenia was investigated by the determination of Annexin-V binding to freshly isolated neutrophils or whole blood samples from these patients with SDS. In contrast to our observations in GSD1b or Barth syndrome,15,16 no enhanced Annexin-V binding or any samples from these patients with SDS. In a dose-response study over a log range in 3 of the patients with SDS with an abnormal chemotaxis response we found similar bell-shaped curves as well as the same optimal concentration for the induction of motility in the patients' neutrophils compared with control cells (data not shown). Chemotaxis defects did not correlate with ANC scores (Table 1; P = .8), which may indicate that there is no altered motility because of the presence of younger and more immature neutrophils in these patients.

Non-DPH-oxidase activity was preserved in SDS neutrophils of all patients, when tested with a variety of stimuli. Similar findings were made for phagocytosis and killing of Staphylococcus aureus or Escherichia coli (data not shown). Apart from the lack of Annexin-V binding to the circulating blood cells in SDS, a normal NADPH-oxidase activity upon activation by STZ (Figure 1B) or the phorbol ester PMA, and phagocytosis also excluded a death-prone cell type in this disease. We, therefore, believe that the myeloid defect or neutropenia in patients with SDS is unrelated to enhanced cell death or peripheral clearance of the circulating neutrophils.

Neutropenia may be the consequence of bone marrow failure. Overt failure at birth was observed in a single of our SDS patients only.24 Although transfusion-dependent aplastic anemia has been reported at later age during childhood and adolescence,7,8 we did not observe any features of imminent bone marrow failure in any of the other patients with SDS. Colony formation tests (CFU-GM and BFU-E) were performed in 14 patients. BM cells uniformly showed a defective maturation and outgrowth of committed progenitor cells in the hematopoietic lineages tested (Figure 1C), irrespective of the blood cell and differential counts in the circulation (Table 1).

Abnormal hematopoietic progenitor as well as stromal cell function has been previously reported in SDS,17,27 which would indicate that the in vitro culture conditions used remain poor estimations of in vivo BM functionality. However, the results demonstrate intrinsic growth defects, whereby CFU-GM from pediatric control subjects or children with benign autoimmune neutropenia of childhood show normal or slightly increased outgrowth (Figure 1C).

Although some of the BM smears showed hypoplasia, dysplastic features were not present. We observed abnormal cytogenetic findings in 5 of 19 patients with SDS (Table 1). In one case a characteristic isochromosome 7, i(7)(q10), was noted (patient 1). This abnormality seems to be unrelated to myelodysplasia or malignancy, as discussed by us and others before.26,29 Another patient is closely followed because of increased HbF% as a possible sign of marrow failure or dysplasia. BM smears and biopsies repeatedly excluded myelodysplasia. BM cells were tested 46, XY [22] / 45 (-7)[3] (patient 14). During the last year, the blood cell count and differentials have normalized (apart from persisting neutropenia) and HbF% decreased spontaneously. Variability in cytogenetic abnormalities is an intriguing aspect in SDS. Smith et al20 reported the transient appearance of a 20q-deletion in a SDS patient with i(7)(q10) as a nonrandom secondary change in SDS. As described here, we observed del(20q) as the sole feature in the BM of 2 patients in the absence of i(7)(q10) (patients 15 and 20). In the adolescent patient the cytogenetic anomaly disappeared in 2 years. Aplasia, malignant transformation, or progressive disease remained absent during the recent 5 years of follow-up in this patient. Another patient had a mosaic 46, XY / 46, XY t(7;10) abnormality in his blood cells (patient 23); its relevance warrants further study for the potential involvement of the regulation of the SBDS gene or neighboring sequences.

In conclusion, a lack of concordance in hematologic findings among affected siblings and the large variability within a family was noticed before.3 At that time the gene responsible for SDS was not yet identified. Using sequence data from 20 of 23 patients with SDS, we may infer that SDS-like syndromes exist without mutations in the SBDS coding sequence as was suggested previously.10,22,23 In the patients with genetically proven SDS only a small series of mutations make up the genetic defect. Even though our conclusions are based on a relatively small number of patients, we may infer from the genetic homogeneity in our study that a clear genotype-phenotype relationship in SDS does not exist in terms of clinical and hematologic parameters.

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