



Adenosine Deaminase Deficiency

Synonyms: ADA Deficiency, ADA1 Deficiency, ADA-Related Immune Deficiency, Adenosine Deaminase 1 Deficiency

Michael Hershfield, MD¹ and Teresa Tarrant, MD²

Created: October 3, 2006; Updated: March 7, 2024.

Summary

Clinical characteristics

Adenosine deaminase (ADA) deficiency is a systemic purine metabolic disorder that primarily affects lymphocyte development, viability, and function. The ADA deficiency phenotypic spectrum includes typical early-onset severe combined immunodeficiency (ADA-SCID), diagnosed in infancy (about 80% of individuals), and less severe "delayed" or "late-onset" combined immunodeficiency (ADA-CID), diagnosed in older children and adults (15%-20% of individuals). Some healthy individuals who are deficient in red blood cell ADA (termed "partial ADA deficiency") have been discovered by screening populations or relatives of individuals with ADA-SCID.

Newborn screening (NBS) for SCID uses extracts from Guthrie card dried blood spots to measure T-cell receptor excision circle (TREC) DNA by polymerase chain reaction (PCR). Screening specific for ADA deficiency can also be performed by detection of elevated levels of adenosine (Ado) and deoxyadenosine (dAdo) by tandem mass spectrometry (TMS). Both techniques can identify ADA-SCID before affected infants become symptomatic.

Untreated ADA-SCID presents as life-threatening opportunistic illnesses in the first weeks to months of life with poor linear growth and weight gain secondary to persistent diarrhea, extensive dermatitis, and recurrent pneumonia. Skeletal abnormalities affecting ribs and vertebra, pulmonary alveolar proteinosis, hemolytic anemia, neurologic abnormalities, and transaminitis may also suggest untreated ADA-SCID. Characteristic immune abnormalities are lymphocytopenia (low numbers of T, B, and NK cells) combined with the absence of both humoral and cellular immune function. If immune function is not restored with enzyme replacement therapy (ERT), gene therapy, or hematopoietic stem cell transplantation (HSCT), children with ADA-SCID rarely survive beyond age one to two years.

NBS for SCID does not identify individuals with the ADA-CID phenotype whose TREC numbers are above the threshold values of most screening laboratories. However, ADA-CID is identified by TMS NBS since the ADA

Author Affiliations: 1 Professor of Medicine and Biochemistry, Duke University Medical Center, Durham, North Carolina; Email: michael.hershfield@duke.edu. 2 Associate Professor of Medicine, Duke University Medical Center, Durham, North Carolina; Email: teresa.tarrant@duke.edu.

Copyright © 1993-2024, University of Washington, Seattle. GeneReviews is a registered trademark of the University of Washington, Seattle. All rights reserved.

substrates Ado and dAdo are increased. As TMS NBS for Ado/dAdo is not yet widely performed, individuals with ADA-CID are more often clinically diagnosed between ages one and ten years ("delayed" onset), or less often in the second to fourth decades ("late"/"adult" onset). Because the immunologic abnormalities are less pronounced than those of ADA-SCID, infections in ADA-CID may not be life-threatening and include recurrent otitis media, sinusitis, upper respiratory infections, and human papilloma viral infections. Untreated individuals with ADA-CID can develop over time chronic pulmonary disease, autoimmunity, atopic disease with elevated immunoglobulin E, and malignancy.

Diagnosis/testing

The diagnosis of ADA deficiency is established in a proband with suggestive findings either by biochemical testing showing <1% of ADA catalytic activity in red blood cells or in extracts of dried blood spots (valid in untransfused individuals), or by molecular genetic testing identifying biallelic pathogenic variants in *ADA*. Frequently, both types of testing are performed.

Management

Treatment of manifestations: Newborns with an abnormal NBS result suggestive of ADA-SCID (by either method) require immediate protection from risk factors for infection and referral for a subspecialty immunology evaluation at a center with expertise in both diagnosis of SCID and its genetic causes and SCID treatment protocols. Symptomatic treatment involves treatment of infections and use of immunoglobulin infusions and antibiotics, particularly prophylaxis against *Pneumocystis jirovecii* pneumonia (formerly *Pneumocystis carinii*) and fungal infections. Prophylaxis against viral infections depends upon exposure and requires frequent surveillance via viral PCR-based testing, with appropriate targeted virus-specific therapy if present.

Targeted therapies: Correcting the ADA deficiency either systemically or selectively in lymphoid cells employs one of three options: (1) enzyme replacement therapy (ERT) by intramuscular administration of PEGylated ADA, (2) allogeneic HSCT, or (3) autologous hematopoietic stem cell ADA gene therapy (HSC-GT) – the latter two are curative. Often, ERT is initiated first to rapidly correct the metabolic defect and to protect against serious infections as well as neurologic/behavioral abnormalities. It is discontinued at the time HSCT or HSC-GT is performed.

Surveillance: The following evaluations are recommended to monitor existing and emerging clinical manifestations and the response to targeted treatment and supportive care: (1) absolute lymphocyte subset counts (T, B, NK cells), quantitative serum immunoglobulin levels, and various in vitro tests of cellular and humoral immune function; (2) total red blood cell deoxyadenosine nucleotides (dAXP) and, if on ERT, plasma ADA activity; and (3) screening for Epstein-Bar virus (EBV)-related lymphoma or other lymphomas after age three years, particularly when lymphocyte counts are declining while on prolonged ERT.

Agents/circumstances to avoid: To ensure the safety of the infant/older individual with ADA deficiency while treatment to achieve immunocompetence is pending, parents and other care providers need to avoid the following risks of infection: (1) breastfeeding and breast milk until maternal CMV status is established by CMV serologies; (2) exposure to young children, sick contacts, individuals with cold sores, crowded enclosed spaces, and sources of aerosolized fungal spores such as areas of construction or soil manipulation; (3) live viral vaccines for the affected infant as well as household contacts; and (4) transfusion of non-irradiated blood products.

Medications to avoid include adenine arabinoside, a substrate for ADA, as an antiviral agent and/or as chemotherapy of malignancies; and pentostatin, a potent ADA inhibitor used to treat some lymphoid malignancies, which would be ineffective in persons with ADA deficiency and would interfere with PEGylated ADA.

Evaluation of relatives at risk: In an at-risk fetus, when the *ADA* pathogenic variants causing *ADA*-SCID in the family are known, prenatal genetic testing may be performed to help prepare for optimal management of an affected infant at birth (i.e., identification of a center with expertise in SCID treatment protocols that can help initiate ERT and the search for an HSCT donor and explain ways to ensure the safety of the infant while awaiting HSCT).

If prenatal testing has not been performed, an at-risk newborn clinically suspected of SCID should immediately be placed in an appropriate environment to reduce the risk of infection, and the following testing should be performed before administration of a blood transfusion to allow earliest possible diagnosis and initiation of treatment: identification of the *ADA* pathogenic variants and measurement of ADA catalytic activity and level of dAXP in red blood cells.

Therapies under investigation: Various approaches to HSC-GT are under investigation.

Genetic counseling

ADA deficiency is inherited in an autosomal recessive manner. If both parents are known to be heterozygous for an *ADA* pathogenic variant, each sib of an affected individual has at conception a 25% chance of being affected, a 50% chance of being an asymptomatic carrier, and a 25% chance of inheriting neither of the familial pathogenic variants. An individual who inherits two pathogenic *ADA* variants will have either *ADA*-SCID or a delayed or late-onset *ADA*-CID phenotype that correlates with the least severe *ADA* pathogenic variant inherited. Once the *ADA* pathogenic variants have been identified in an affected family member, carrier testing for at-risk relatives and prenatal and preimplantation genetic testing are possible.

GeneReview Scope

Adenosine Deaminase Deficiency: Phenotypic Spectrum

| Phenotype ^{1, 2} | Proportion of Persons w/ <i>ADA</i> Deficiency | Comment |
|----------------------------------------------------------------------------------------------|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Typical early-onset severe combined immunodeficiency (<i>ADA</i> -SCID) | ~80% | Diagnosed in infancy |
| Less severe "delayed"/"late-onset" combined immunodeficiency (<i>ADA</i> -CID) ³ | 15%-20% | Diagnosed in older children & adults |
| Benign "partial <i>ADA</i> deficiency" | -- | Discovered by screening populations or relatives of persons w/ <i>ADA</i> -SCID for deficiency of erythrocyte <i>ADA</i> activity |

ADA = adenosine deaminase

- 1. For other genetic causes of combined immunodeficiency, see Differential Diagnosis.
- 2. For *ADA* enzyme levels associated with these phenotypes, see Genotype-Phenotype Correlations.
- 3. *ADA*-CID may also be referred to as "leaky SCID."

Note: Deficiency of adenosine deaminase (*ADA*, also referred to as adenosine deaminase 1, or *ADA1*) is caused by pathogenic variants in *ADA*. It must be distinguished from the phenotypically distinct disorder deficiency of [adenosine deaminase 2](#) (*DADA2*), associated with pathogenic variants in *ADA2* (see Nomenclature and Differential Diagnosis).

Diagnosis

Adenosine deaminase (*ADA*) deficiency cannot be diagnosed solely on clinical grounds. The Primary Immune Deficiency Treatment Consortium (PIDTC) has established laboratory-based definitions for severe combined immunodeficiency (SCID) [Dvorak et al 2023a, Dvorak et al 2023b].

Suggestive Findings

The two scenarios in which ADA deficiency may be considered are a positive newborn screening result and a symptomatic individual of any age with suggestive clinical and laboratory findings of combined immunodeficiency (CID). In both scenarios, individuals identified warrant immediate subspecialty immunology evaluation and steps taken to ensure the safety of a baby or older individual pending establishment of the diagnosis and treatment.

Scenario 1: Positive Newborn Screening Result

T-cell receptor excision circles (TRECs) to detect T-cell lymphopenia. As of December 10, 2018, all newborns in the United States, including all 50 states, the District of Columbia, and the Navajo Nation, are screened for a group of conditions characterized by SCID.

Currently, SCID newborn screening (NBS) uses a blood spot to measure TRECs to detect T-cell lymphopenia [van der Spek et al 2015]. An abnormal NBS (low/absent TRECs) indicates clinically significant autologous T-cell lymphocytopenia ($<1,500$ T cells/ μ L). In the US, the NBS agency in each state determines the TREC threshold that indicates possible SCID. Note: Historically, about 15% of all SCID results from ADA deficiency, whereas the frequency appears to be about 12% among newborns identified as having SCID by TREC screening [Dvorak et al 2023a, Dvorak et al 2023b].

Neonatal screening specifically for ADA deficiency can be accomplished by using tandem mass spectrometry (TMS) to detect elevated levels of the ADA enzyme substrates adenosine (Ado) and deoxyadenosine (dAdo) in extracts of dried blood spots (i.e., Guthrie cards) [Azzari et al 2011, Speckmann et al 2012, la Marca et al 2013, Malvagia et al 2021, Hartog et al 2022]. TMS screening for ADA deficiency is inexpensive, highly accurate and sensitive, and capable of identifying individuals with a delayed or late-onset phenotype (ADA-CID) who may be missed by TREC screening [Speckmann et al 2012, la Marca et al 2013, Hartog et al 2022].

Note: NBS for ADA deficiency by TMS, developed in Italy, is now used in several other countries in Europe and Scandinavia, as well as in several states in the US and provinces in Canada; wider use may be anticipated.

Newborns with an abnormal NBS result (by either method) **require immediate subspecialty immunology evaluation** at a center with expertise in the diagnosis of SCID and its genetic causes, and in SCID treatment protocols (see Management, Treatment of Manifestations).

This chapter specifically focuses on ADA-related SCID (ADA-SCID), one genetic cause of SCID. For other genetic causes of an abnormal NBS possibly indicating SCID, see Differential Diagnosis.

Ensuring the Safety of the Baby

The safety of the baby must be ensured pending establishment of the diagnosis and treatment. Parents and other care providers for all infants with a positive NBS need to avoid all of the following:

- Breast-feeding and breast milk, until maternal CMV status is established by CMV serologies. CMV is a chronic infection and intermittent viral shedding in various bodily fluids occurs unpredictably. If maternal CMV serology is negative, breast milk may be considered safe for feeding.

Note: Use of pasteurized breast milk while the infant is being prepared for HSCT remains controversial given the severe negative effects of CMV infection in the outcome of HSCT.

- Exposure to young children, sick contacts, or individuals with cold sores in order to decrease the risk of transmission of disease to the infant
- Crowded enclosed spaces due to risk of infectious exposure

- Live viral vaccines for the infant as well as household contacts until after immunocompetence is restored following HSCT or gene therapy
- Transfusion of non-irradiated blood products [Dorsey et al 2017]. Use of only leukoreduced and CMV-negative, irradiated blood products is recommended.
- Areas of construction or soil manipulation as they increase the risk for fungal exposure.

Laboratory Findings

Laboratory findings that support (but are not specific to) the diagnosis of *ADA*-SCID include the following **immunophenotyping**:

- Lymphocyte subsets identified by flow cytometric analysis of confirmed autologous T cells [Flinn & Gennery 2018]
 - Markedly reduced numbers of T, B, and NK cell lymphocyte subsets compared to age-matched normal controls (designated T⁻B⁻NK⁻)
 - Virtual absence of naïve CD45RA⁺ cells; however, mature CD45RO⁺ lymphocytes can be present in reduced numbers.
- Lymphocyte functional tests
 - Absence of specific antibody responses to vaccines and infectious agents
 - Absence of in vitro T cell responses to mitogens (i.e., <10% of normal proliferation of lymphocytes to the mitogen phytohemagglutinin [PHA] having excluded maternal engraftment) and/or anti-CD3 antibodies.

Biochemical and molecular genetic testing are used to establish the diagnosis (see Establishing the Diagnosis).

Family History

Family history is consistent with autosomal recessive inheritance (e.g., affected sibs and/or parental consanguinity). Absence of a known family history does not preclude the diagnosis. Note: Families with *ADA* pathogenic variants segregating with SCID may have a history of unexplained infant mortality.

Scenario 2: Symptomatic Individual

A symptomatic individual may present who had low TRECs on NBS or a positive TMS but did not receive recommended follow-up testing to confirm SCID, or with clinical and laboratory findings suggesting CID in whom NBS was non-diagnostic for SCID or in whom NBS was not performed.

Clinical Findings

Clinical findings that support (but are not specific to) the diagnosis of *ADA*-related SCID or CID include the following, by age:

- Infancy (typical early-onset *ADA*-SCID)
 - Failure to thrive
 - Absence of lymphoid tissues (tonsils, lymph nodes)
 - Opportunistic infections (viral, fungal, or bacterial)
 - Persistent diarrhea
 - Extensive dermatitis
 - Recurrent pneumonia
- Childhood (less severe delayed or late-onset *ADA*-CID)
 - Recurrent otitis media
 - Sinusitis

- Frequent/recurrent upper respiratory infections
- Chronic pulmonary insufficiency
- Frequent/recurrent viral infections including warts due to human papillomavirus
- Allergies or autoimmunity (serum immunoglobulin E level often elevated)

Laboratory Findings

Laboratory findings that support the diagnosis of *ADA*-CID include the following:

- **Newborn screening**
 - Individuals with delayed or late-onset *ADA*-CID may have TRECs in the normal range at birth [Speckmann et al 2012, la Marca et al 2013, Kahwash et al 2021, Hartog et al 2022].
 - Reduced levels of a B-cell lymphocyte marker, kappa-deleting recombination excision circles (KRECs), have also been found in DNA from dried blood spots of individuals with delayed or late-onset *ADA*-CID [Speckmann et al 2012].
- **Immunophenotype**
 - Lymphopenia: the total blood lymphocyte count is usually $<500/\mu\text{L}$ (normal for neonates: 2,000 to $>5,000/\mu\text{L}$), a finding present at birth, which at that time may not be recognized as abnormal.
 - All major lymphoid lineages (T, B, and NK cells) are depleted as demonstrated by flow cytometry.
 - In vitro lymphocyte function, as measured by proliferative response to mitogens and antigens, is low or absent.
 - Serum immunoglobulins are low and no specific antibody response to infections and immunizations is observed. However, individuals with a delayed or late-onset phenotype may have elevated serum immunoglobulin E levels.
 - Neutropenia and myeloid dysplasia have been observed [Sokolic et al 2011, Kim et al 2019, Kohn et al 2019].

Imaging Findings

In children less than age seven months, radiologic findings can include scapular spurring, scapular squaring, and costochondral cupping [Verhagen et al 2020]. The latter may aid in differentiating *ADA*-SCID from non-*ADA*-SCID, with a sensitivity of ~92% (22/24) and specificity of ~80% (15/19) reported in a single-center study of radiologic abnormalities [Verhagen et al 2020].

Family History

Family history is consistent with autosomal recessive inheritance (e.g., affected sibs and/or parental consanguinity). Absence of a known family history does not preclude the diagnosis. Note: Families with *ADA* pathogenic variants segregating with SCID may have a history of unexplained infant mortality.

Establishing the Diagnosis

The diagnosis of *ADA* deficiency is **established** in a proband with suggestive findings either by biochemical testing or by molecular genetic testing. Frequently, both types of testing are performed. Of note, turnaround time, which varies among laboratories, should be considered when determining the order of testing.

Biochemical Testing

Biochemical testing for *ADA* deficiency should be performed as soon as possible after a diagnosis of SCID or CID has been established following a positive NBS TREC or TMS screen, particularly when follow-up testing shows $\text{T}^- \text{B}^- \text{NK}^-$ lymphocytopenia [Hershfield & Mitchell 2001, Hartog et al 2022].

- **Testing of ADA catalytic activity in red blood cells (RBCs)** is offered by several reference laboratories in the US. An abnormal test result is <1% of normal ADA catalytic activity in hemolysates or in extracts of dried blood spots (DBS) prepared with ethylenediaminetetraacetic acid (EDTA) or heparin-anticoagulated blood (applies to blood samples obtained from untransfused individuals).

Note: (1) In individuals who have received RBC transfusion(s) prior to biochemical testing, deficient ADA catalytic activity can be demonstrated in extracts of non-erythroid cells (e.g., fibroblasts) because individuals with SCID have insufficient blood mononuclear cells for analysis. However, this approach is now rarely used, as molecular genetic testing has become widely available. (2) Analysis of ADA catalytic activity in plasma is not useful for diagnosis of ADA-SCID because:

- ADA catalytic activity in plasma is much lower than that in cells, even in healthy individuals;
- Depending on the assay conditions, most ADA catalytic activity in plasma is due to the secreted enzyme ADA2, encoded by *ADA2* (see Differential Diagnosis).

- **Quantitation of deoxyadenosine triphosphate (dATP) or total deoxyadenosine nucleotides (dAXP) in RBCs.** Normal RBCs contain essentially no dAXP. The finding of elevated levels of dATP or dAXP in RBCs is pathognomonic for immune deficiency caused by ADA deficiency [Hershfield & Mitchell 2001, Kohn et al 2019].

- Levels of dAXP >0.1 $\mu\text{mol/mL}$ in packed RBCs (or >1%-2% of total adenine nucleotides) is abnormal.

Note: (1) In individuals with clinical findings of SCID or CID who have recently been transfused, any elevation of dAXP in RBCs strongly suggests ADA deficiency. (2) Analysis of dATP or dAXP in RBCs is presently performed only by specialty laboratories, including the authors' CLIA certified laboratory at Duke University (see Chapter Notes).

Molecular Genetic Testing

The molecular diagnosis of ADA deficiency **is established** in a proband when biallelic pathogenic (or likely pathogenic) variants in *ADA* are identified by molecular genetic testing (see Table 1).

Note: (1) Per ACMG/AMP variant interpretation guidelines, the terms "pathogenic variant" and "likely pathogenic variant" are synonymous in a clinical setting, meaning that both are considered diagnostic and can be used for clinical decision making [Richards et al 2015]. Reference to "pathogenic variants" in this *GeneReview* is understood to include any likely pathogenic variants. (2) Identification of biallelic *ADA* variants of uncertain significance (or of one known *ADA* pathogenic variant and one *ADA* variant of uncertain significance) does not establish or rule out the diagnosis.

Molecular genetic testing approaches can include a combination of **gene-targeted testing** (multigene panel) and **comprehensive genomic testing** (exome sequencing, genome sequencing). Gene-targeted testing requires that the clinician determine which gene(s) are likely involved (see Option 1), whereas comprehensive genomic testing does not (see Option 2).

Option 1

An immunodeficiency or SCID multigene panel that includes *ADA* and other genes of interest (see Differential Diagnosis) is most likely to identify the genetic cause of the condition while limiting identification of variants of uncertain significance and pathogenic variants in genes that do not explain the underlying phenotype. Note: (1) The genes included in the panel and the diagnostic sensitivity of the testing used for each gene vary by laboratory and are likely to change over time. (2) Some multigene panels may include genes not associated with the condition discussed in this *GeneReview*. (3) In some laboratories, panel options may include a custom laboratory-designed panel and/or custom phenotype-focused exome analysis that includes genes specified by the

clinician. (4) Methods used in a panel may include sequence analysis, deletion/duplication analysis, and/or other non-sequencing-based tests.

For an introduction to multigene panels click [here](#). More detailed information for clinicians ordering genetic tests can be found [here](#).

Option 2

Comprehensive genomic testing does not require the clinician to determine which gene is likely involved. **Exome sequencing** is most commonly used; **genome sequencing** is also possible.

For an introduction to comprehensive genomic testing click [here](#). More detailed information for clinicians ordering genomic testing can be found [here](#).

Table 1. Molecular Genetic Testing Used in Adenosine Deaminase Deficiency

| Gene ¹ | Method | Proportion of Pathogenic Variants ² Identified by Method |
|-------------------|----------------------------------------------------------|---------------------------------------------------------------------|
| ADA | Sequence analysis ³ | >90%-95% ⁴ |
| | Gene-targeted deletion/duplication analysis ⁵ | ~5%-10% ⁴ |

1. See Table A. Genes and Databases for chromosome locus and protein.

2. See Molecular Genetics for information on variants detected in this gene.

3. Sequence analysis detects variants that are benign, likely benign, of uncertain significance, likely pathogenic, or pathogenic. Variants may include missense, nonsense, and splice site variants and small intragenic deletions/insertions; typically, exon or whole-gene deletions/duplications are not detected. For issues to consider in interpretation of sequence analysis results, click [here](#).

4. Data derived from the subscription-based professional view of Human Gene Mutation Database [Stenson et al 2020]

5. Gene-targeted deletion/duplication analysis detects intragenic deletions or duplications. Methods used may include a range of techniques such as quantitative PCR, long-range PCR, multiplex ligation-dependent probe amplification (MLPA), and a gene-targeted microarray designed to detect single-exon deletions or duplications. Exome and genome sequencing may be able to detect deletions/duplications using breakpoint detection or read depth; however, sensitivity can be lower than gene-targeted deletion/duplication analysis.

Clinical Characteristics

Clinical Description

Adenosine deaminase (ADA) deficiency (also referred to as adenosine deaminase 1 deficiency, or ADA1 deficiency) is a systemic purine metabolic disorder that primarily affects lymphocyte development, viability, and function [Hirschhorn 1999, Hershfield & Mitchell 2001, Hershfield 2004, Whitmore & Gaspar 2016]. ADA is expressed in all cells, but is most highly expressed in lymphocytes; thus, in some individuals, ADA deficiency can affect non-lymphoid organs such as the lungs, liver, kidneys, and nervous system (resulting in behavioral abnormalities) [Flinn & Gennery 2018, Grunebaum et al 2023].

The phenotypic spectrum of ADA deficiency includes typical early-onset severe combined immunodeficiency (ADA-SCID), diagnosed in infancy (about 80% of individuals), and less severe "delayed" or "late-onset" combined immunodeficiency (ADA-CID), diagnosed in older children and adults (15%-20% of individuals). Benign "partial ADA deficiency," which has no associated phenotype, was discovered when populations or relatives of individuals with ADA-SCID were screened for deficiency of ADA catalytic activity in red blood cells.

Typical Early-Onset Severe Combined Immunodeficiency (ADA-SCID)

The clinical findings in infants with typical early-onset ADA-SCID are similar to those observed in untreated SCID resulting from other genetic causes [Dvorak et al 2013, Shearer et al 2014, Dvorak et al 2023a, Dvorak et al 2023b]. Affected children present in the first weeks to months of life with poor growth and opportunistic

infections associated with marked lymphocytopenia and the absence of both humoral and cellular immune function. The diagnosis of ADA-SCID is often made within the first three months of life and usually by age 12 months [Kuo et al 2020].

Persistent diarrhea, extensive dermatitis, recurrent pneumonia, and other life-threatening illnesses caused by opportunistic infections occur frequently. As a result, poor weight gain and linear growth are common.

Noninfectious lung disease, frequently associated with alveolar proteinosis, appears to occur more frequently in individuals with ADA-SCID than with other genetic causes of SCID [Booth et al 2012, Grunebaum et al 2012, Kuo et al 2020]. Pulmonary dysfunction has also been identified using the effort-independent technique of impulse oscillometry [Komarow et al 2015]. Historically, about 30% of individuals with ADA deficiency have developed chronic pulmonary complications including asthma, bronchiectasis, bronchiolitis obliterans, and interstitial lung disease [Kuo et al 2020, Grunebaum et al 2023].

Physical findings include growth failure and the absence of lymphoid tissues (tonsils, lymph nodes). Thymus shadow is absent on radiographs. The characteristic radiographic changes of anterior rib cupping, scapular spurring, and other skeletal abnormalities that are present at the time of diagnosis in about 50% of individuals with ADA-SCID [Verhagen et al 2020] may resolve after treatment [Manson et al 2013].

In addition to marked depletion of T, B, and NK cell lymphocytes, some individuals with ADA-SCID may show reduced neutrophil counts and bone marrow abnormalities including myeloid dysplasia and hypocellularity [Sokolic et al 2011, Kim et al 2019, Kuo et al 2020].

Other system involvement. Abnormal liver function tests and various neurologic or behavioral abnormalities, which may be clinically significant, can occur both before and after immunodeficiency is diagnosed [Bollinger et al 1996, Tanaka et al 1996, Rogers et al 2001, Albuquerque & Gaspar 2004, Nofech-Mozes et al 2007, Sauer et al 2017, Kuo et al 2020, Grunebaum et al 2023]. The prevalence of non-lymphoid system involvement is variable and may be influenced by infections, antibiotic therapy, and other risk factors. The effect of more rapid diagnosis and earlier institution of specific treatment (i.e., enzyme replacement therapy, hematopoietic stem cell transplantation, or gene therapy) has yet to be determined.

- **Liver.** Although hepatic dysfunction tends to be mild, abnormal liver function tests may be an early sign in an otherwise asymptomatic child with ADA deficiency [Kohn et al 2019].
- **Neurologic/behavioral abnormalities,** including sensorineural hearing loss, seizures, motor dysfunction, attention-deficit/hyperactivity disorder, aggression, and social problems were observed in about 45% of 64 children in the [US Immunodeficiency Network \(USIDNET\)](#) registry of individuals with ADA deficiency [Kuo et al 2020]. Hearing loss was found in 18 (28%) of these individuals. Of note: Neurologic abnormalities may be present at the time of diagnosis or may appear during treatment, including enzyme replacement therapy, hematopoietic stem cell transplantation, or gene therapy [Hönig et al 2007, Sauer et al 2017, Grunebaum et al 2023].
- **Dermatofibrosarcoma protuberans (DFSP),** a rare malignant skin tumor, has been identified in several individuals with ADA-SCID [Kesserwan et al 2012, Kuo et al 2020, Wahjudi et al 2021]. DFSP was found in 12 of 64 individuals in the USIDNET registry [Kuo et al 2020]. DFSP may be recurrent and multifocal, but the natural history of DFSP in individuals with ADA deficiency is not fully known.
- **Atypical hemolytic uremic syndrome** as a presentation of ADA-SCID has been reported [Nikolajeva et al 2015, Bogdał et al 2021].

Prognosis. If immune function is not restored, children with ADA-SCID rarely survive beyond age one to two years.

Delayed or Late-Onset Combined Immunodeficiency (ADA-CID)

Approximately 15%-20% of children with ADA deficiency have a "delayed" onset of clinical manifestations, usually diagnosed between ages one and ten years. Rarely, individuals with ADA-CID are diagnosed in the second to fourth decades ("late" or "adult" onset). Because the immunologic abnormalities are less pronounced than in ADA-SCID, these individuals are usually referred to as having combined immunodeficiency (CID), or sometimes "leaky" SCID [Shearer et al 2014, Dvorak et al 2023a].

Infections in ADA-CID may initially be less severe than in individuals with ADA-SCID. Recurrent otitis media, sinusitis, and upper respiratory infections are common. Palmar and plantar warts may be persistent. Older individuals have presented with unusual papillomaviral infections [Antony et al 2002, Artac et al 2010, Grunebaum et al 2023].

While individuals with ADA-CID may survive undiagnosed into the first decade of life or beyond, the longer ADA deficiency goes unrecognized, the more immune function deteriorates and the more likely there will be sequelae of chronic recurrent respiratory infections and other types of infection. By the time of diagnosis, these individuals often have chronic pulmonary insufficiency and autoimmune phenomena, including cytopenias and autoantibodies [Sauer et al 2012]. Allergies and elevated serum concentration of immunoglobulin E are common.

Benign Partial ADA Deficiency

Screening of populations and families of probands with ADA-SCID has identified some healthy individuals with very low or absent ADA catalytic activity in red blood cells but greater levels of ADA activity (2% to >50% of normal) in nucleated cells (see Genotype-Phenotype Correlations). Importantly, total deoxyadenosine nucleotides (dAXP) or deoxyadenosine triphosphate (dATP) are not elevated in red blood cells in these individuals, in contrast to the elevation found in all individuals with ADA deficiency with immune deficiency (SCID or CID). This benign condition is compatible with normal immune function and good health [Hershfield 2004, Flinn & Gennery 2018].

Nomenclature

ADA-SCID may also be referred to as "ADA-related immunodeficiency" based on the naming approach proposed by Biesecker et al [2021] to delineate mendelian genetic disorders.

The protein encoded by *ADA* (chromosome locus 20q13.12) that is absent in ADA-SCID has, in recent years, been referred to as adenosine deaminase 1 (ADA1) to distinguish it from another protein with adenosine deaminase activity, adenosine deaminase 2 (ADA2), encoded by *ADA2* (chromosome locus 22q11.1). Inherited [deficiency of ADA2](#) (DADA2) is a separate disorder that is phenotypically distinct from ADA-SCID.

ADA-CID may also be referred to as "leaky" SCID.

Genotype-Phenotype Correlations

In the era of newborn screening based on detection of T-cell receptor excision circles (TRECs) / kappa-deleting recombination excision circles (KRECs) to identify lymphopenia and, increasingly, tandem mass spectrometry (TMS) to detect elevated levels of ADA substrates, ADA deficiency is often identified in asymptomatic infants. Given the broad clinical spectrum of ADA deficiency, determining the diagnosis, prognosis, and need for immediate treatment are challenges for physicians who may have limited experience with ADA deficiency. In this situation, useful guidance can be provided by understanding the correlation between ADA genotype, level of dAXP in red blood cells, ADA catalytic activity in red blood cells, and clinical phenotype. These relationships were defined prior to the era of newborn screening when the natural history of ADA deficiency was usually evident at the time of diagnosis.

The relationship between the *ADA* genotype and clinical phenotype was assessed by systematically expressing cDNAs with missense variants derived from affected individuals in an *E coli* strain lacking *ada* (*E coli* gene homologous to *ADA*) [Arredondo-Vega et al 1998, Hershfield 2003]. *ADA* variants were then grouped according to their expressed *ADA* catalytic activity (compared with *ADA* catalytic activity expressed from the normal human *ADA* cDNA):

- **Group 0.** "Null" variants (deletion, frameshift, or nonsense variants) that completely eliminate functional *ADA* catalytic activity
- **Groups I-IV.** Missense variants that express increasing *ADA* catalytic activity in the *E coli* system:
 - Group I. <0.05% of normal
 - Group II. 0.1%-0.2% of normal
 - Group III. 0.3%-0.6% of normal
 - Group IV. ~2%-28% of normal
- **Splice site variants.** Not ranked, as a low level of normal splicing may result in variable levels of functional *ADA* catalytic activity

This ranking system was then applied to 52 clinically diverse individuals with 43 genotypes comprising 42 different *ADA* variants [Arredondo-Vega et al 1998, Hershfield 2003]. Clinical phenotype correlated with total *ADA* catalytic activity expressed by both alleles making up an individual's genotype* as follows:

- Individuals with *ADA*-SCID had both variants from Groups 0 or I.
- Individuals with *ADA*-CID were compound heterozygotes with at least one variant from Groups II or III.
- Healthy individuals with benign partial *ADA* deficiency were compound heterozygotes with at least one variant from Group IV.

* In individuals with compound heterozygosity for two different *ADA* pathogenic variants, the pathogenic variant associated with a less severe phenotype determines the phenotype.

An inverse correlation existed between expressed *ADA* catalytic activity in *E coli* and the level of dAXP in red blood cells found at diagnosis (in untreated individuals). In the authors' experience over the past three decades, red blood cell dAXP levels (which are normally undetectable) vary by phenotype (see Table 2).

Table 2. Deoxyadenosine Nucleotides (dAXP) Levels by Phenotype

| Phenotype | RBC dAXP Concentration ¹ | dAXP as Percent of RBC Adenine Nucleotides |
|-------------------------------|---------------------------------------------|--------------------------------------------|
| <i>ADA</i> -SCID | ~0.35 to >1.5 $\mu\text{mol/mL}$ packed RBC | ~20% to >70% |
| <i>ADA</i> -CID | ~ 0.1 to 0.3 $\mu\text{mol/mL}$ packed RBC | 2%-3% to ~25% |
| Partial <i>ADA</i> deficiency | Undetectable to <0.1 $\mu\text{mol/mL}$ RBC | 0 to ~2% |

CID = combined immunodeficiency; dAXP = deoxyadenosine nucleotides; RBC = red blood cell; SCID = severe combined immunodeficiency

1. In untreated individuals

Several individuals with *ADA* deficiency have been reported in whom the relationship of genotype to phenotype was modulated by mosaicism for reversion of *ADA* pathogenic variants in lymphoid cells [Hirschhorn et al 1994, Hirschhorn et al 1996, Ariga et al 2001a, Arredondo-Vega et al 2002, Liu et al 2009, Moncada-Vélez et al 2011].

Prevalence

ADA deficiency is estimated to occur in 1:500,000 live births [Kuo et al 2020]. As information from newborn screening becomes available, estimates of the incidence of *ADA* deficiency may change.

All racial and ethnic groups are affected.

Prevalence is higher in certain populations (e.g., Amish, Canadian Mennonite, Inuit, and Somali) due to founder pathogenic variants (see Table 5).

Genetically Related (Allelic) Disorders

No phenotypes other than those described in this *GeneReview* are associated with germline pathogenic variants in *ADA*.

Differential Diagnosis

Table 3 lists selected genes known to be associated with typical severe combined immunodeficiency (SCID).

Note: Other genes (not included in Table 3) have been associated with SCID-like phenotypes in rare instances.

Table 3. Typical Severe Combined Immunodeficiency (SCID): Genetic Causes

| Gene(s) | Disorder | MOI | Lymphocyte Phenotype | | | Comments | NBS |
|--------------------------------------------------------------------|------------------------------------------------------------------------|-----|----------------------|---|----|---------------------------------------------------------------------------------------------------------------------------------|----------------|
| | | | T | B | NK | | |
| Types of typical SCID w/identical clinical presentations | | | | | | | |
| <i>IL2RG</i> | X-linked SCID | XL | – | + | – | Affects males only; atypical X-SCID can be observed ¹ ; may be assoc w/Omenn syndrome. ² | + |
| <i>JAK3</i> | <i>JAK3</i> -SCID (OMIM 600802) | AR | – | + | – | Affects both males & females. | + |
| <i>IL7R</i> | <i>IL7R</i> -SCID (OMIM 608971) | AR | – | + | + | | + |
| Other types of typical SCID (ordered alphabetically by assoc gene) | | | | | | | |
| <i>ADA</i> | ADA deficiency (topic of this <i>GeneReview</i> ; incl for comparison) | AR | – | – | – | Less severe "delayed" or "late-onset" CID if ADA deficiency is incomplete | ± ³ |
| <i>AK2</i> | Reticular dysgenesis (OMIM 267500) | AR | – | – | – | Rare | + |
| <i>CD3D</i> <i>CD3E</i> <i>CD247</i> (<i>CD3Z</i>) | TCR deficiency (OMIM 615617, 615615, 610163) | AR | –/ Low | + | + | Rare | + |
| <i>CORO1A</i> | <i>CORO1A</i> deficiency (OMIM 615401) | AR | –/ Low | ± | ± | Rare | + |
| <i>DCLRE1C</i> | SCID Athabaskan (OMIM 602450) | AR | – | – | + | 10% carrier rate among Athabaskan-speaking Native Americans (e.g., Navajo, Apache); may be assoc w/Omenn syndrome. ² | + |
| <i>PNP</i> | PNP deficiency ⁴ | AR | – | ± | ± | Rare (1%-2% of persons w/CID); affects both males & females. | ± ⁵ |
| <i>PRKDC</i> | DNAPKCS deficiency (OMIM 615966) | AR | – | – | + | Rare | + |

Table 3. continued from previous page.

| Gene(s) | Disorder | MOI | Lymphocyte Phenotype | | | Comments | NBS |
|----------------------------|----------------------------------|-----|----------------------|---|----|--------------------------------------------------------------------------------------------|----------------|
| | | | T | B | NK | | |
| <i>PTPRC</i> (CD45) | CD45 deficiency (OMIM 608971) | AR | – | + | ± | | + |
| <i>RAG1</i> <i>RAG2</i> | RAG-deficient SCID (OMIM 601457) | AR | – | – | + | Atypical X-SCID can be observed ¹ ; may be assoc w/Omenn syndrome. ² | + ⁶ |

Based on the International Union of Immunological Societies expert committee for primary immunodeficiency

ADA = adenosine deaminase; AR = autosomal recessive; CID = combined immune deficiency; MOI = mode of inheritance; NBS = newborn screening; XL = X-linked

1. For immunophenotype information, see [X-Linked Severe Combined Immunodeficiency](#).

2. Omenn syndrome is a clinical phenotype caused by immune dysregulation and characterized by generalized erythroderma, hepatosplenomegaly, lymphadenopathy, elevated serum immunoglobulin E, and/or increased eosinophils. The immunophenotype is CD3⁺ T cells >300 cells/μL in the absence of maternal engraftment.

3. Less severe delayed or late-onset ADA-related combined immunodeficiency (ADA-CID) may be missed by NBS.

4. Schejter et al [2020]

5. PNP deficiency may be missed by NBS. PNP deficiency is detected by TMS [Martín-Nalda et al 2021] or biochemical testing [Schejter et al 2020].

6. Increasingly detected with newborn screening [Kwan et al 2014]

Purine nucleoside phosphorylase (PNP) deficiency (OMIM 613179), an inborn error of purine metabolism that causes autosomal recessive combined immunodeficiency (SCID or CID), is – in some respects – similar clinically and pathophysiologically to ADA deficiency [Hershfield 2004, Schejter et al 2020]. When molecular genetic testing results are not available, individuals with SCID or CID who are suspected of having either disorder should undergo biochemical testing for both ADA deficiency and PNP deficiency in erythrocytes [Schejter et al 2020].

Management

Consensus recommendations for managing severe combined immunodeficiency (SCID) due to adenosine deaminase (ADA) deficiency have been published [Kohn et al 2019, Grunebaum et al 2023]. These guidelines focus on correction of the ADA deficiency and the restoration of immune function. No recommendations or guidelines have been developed for the management of systemic (non-immunologic) abnormalities associated with ADA deficiency, which varies among medical centers and practitioners.

Evaluations Following Initial Diagnosis

To establish the extent of disease and needs in an individual diagnosed with ADA deficiency, the following evaluations are recommended, some of which may have been performed as part of the diagnostic evaluation. The frequency and timing of testing may vary by the treating practitioner and the individual's clinical presentation.

- Consultation with a clinical immunologist with expertise in the diagnosis of SCID, genetic causes of SCID, and SCID treatment protocols
- Identification of specific disease-causing viral, fungal, or bacterial organisms (both normal pathogens and opportunistic agents)
- Complete blood count with differential
- Flow cytometry to quantify lymphocyte subsets (T⁺, B⁺, NK⁺ cells)
- Assessment of humoral immune function by measuring serum immunoglobulins and the titer of specific antibodies related to infections and immunizations

- Evaluation of cellular immune function by in vitro response of blood mononuclear cells to mitogens and antigens
- Liver function testing to detect hepatitis
- Auditory testing for sensorineural hearing loss
- Skeletal radiographs to assess for characteristic bone abnormalities
- Measurement of total deoxyadenosine nucleotide (dAXP) levels in red blood cells to evaluate metabolic severity (see Genotype-Phenotype Correlations). If not already evaluated, ADA sequencing should be obtained to determine genotype.
- Consultation with a medical geneticist, certified genetic counselor, or certified advanced genetic nurse to inform affected individuals and their families about the nature, mode of inheritance, and implications of ADA deficiency in order to facilitate medical and personal decision making
- Assessment of need for community or online resources such as [Parent to Parent](#), social work involvement for parental support, and home nursing referral

Treatment of Manifestations

Symptomatic Treatment

Symptomatic treatment includes:

- Ensuring the safety of the infant/child (see Agents/Circumstances to Avoid);
- Treatment of infections and use of immunoglobulin infusions and antibiotics, particularly prophylaxis against *Pneumocystis jirovecii* pneumonia (formerly *Pneumocystis carinii*) and fungal infections. Prophylaxis against viral infections depends upon exposure and frequent surveillance via viral PCR-based testing with appropriate targeted viral-specific therapy if present.

Targeted Therapies

In GeneReviews, a targeted therapy is one that addresses the specific underlying mechanism of disease causation (regardless of whether the therapy is significantly efficacious for one or more manifestation of the genetic condition); would otherwise not be considered without knowledge of the underlying genetic cause of the condition; or could lead to a cure. —ED

The aim of targeted therapies is to restore a functional immune system, which is essential to preventing the life-threatening manifestations of ADA-SCID. This requires correcting the ADA deficiency either system-wide or selectively in lymphoid cells. At present, the three options for the specific treatment of ADA-SCID are presented in Table 4. Selection of the initial therapy depends on factors such as the age and clinical status of the individual, the expectations and desires of the parents, the availability of the therapy, and the experience and expertise of the treating physicians.

Table 4. Targeted Therapy Options to Restore Immune Function

| Targeted Therapy | Key Advantages | Key Disadvantages | Comment |
|---------------------------------------------------|---------------------------------------------------------|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Enzyme replacement therapy (ERT) w/ PEGylated ADA | Can often be initiated more quickly than HSCT or HSC-GT | Not curative | Recommended as the initial therapy as a bridge until HSCT or HSC-GT can be performed. ^{1, 2} By correcting metabolic abnormalities due to ADA deficiency, ERT can: <ul style="list-style-type: none"> • Prevent opportunistic infections in asymptomatic individuals; • Stabilize & improve clinical status of persons w/serious infections or other disease manifestations. |

Table 4. continued from previous page.

| Targeted Therapy | Key Advantages | Key Disadvantages | Comment |
|--------------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Allogeneic hematopoietic stem cell transplantation (HSCT) | Potentially curative (70% w/matched related donors) | <ul style="list-style-type: none"> Lack of an appropriate matched donor Graft-vs-host disease Graft failure Not all affected persons are suitable candidates. | HSCT from an HLA-identical healthy sib is method of choice for treating all forms of SCID. |
| Autologous hematopoietic stem cell ADA gene therapy (HSC-GT) | Potentially curative | <ul style="list-style-type: none"> Limited availability Different viral vectors have had varied clinical outcomes, incl risk of malignant transformation & transfection efficiency Not all affected persons are suitable candidates. | For those w/ADA-SCID who lack an HLA-identical donor, HSC-GT can be a therapeutic option. |

1. Kohn et al [2019], Grunebaum et al [2023]

2. Kohn et al [2019]

Enzyme Replacement Therapy (ERT) with PEGylated ADA

Between 1990 and 2019, ERT for ADA-SCID was performed with Adagen[®] (pegademase bovine), consisting of bovine ADA isolated from cow intestine and modified ("PEGylated") by attachment of multiple strands of 5 kDa monomethoxypolyethylene glycol (mPEG). In January 2019, Adagen[®] was replaced by Revcovi[®] (elapegamase-lvlr), which is similar but prepared with recombinant bovine ADA.

The US clinical trial that supported FDA approval of Revcovi[®] showed that it was safe and maintained biochemical detoxification and lymphocyte counts in six adults who had previously been treated for an average of 20 years with Adagen[®] [Dorsey et al 2023]. To date, there is little published information about the use of Revcovi[®] as initial therapy in newly diagnosed individuals with ADA-SCID. However, when used according to the package insert, Revcovi[®] was reported to be well tolerated and effective in the management of six infants, five of whom had been identified by newborn screening [Murguia-Favela et al 2023]. The general recommendations of Kohn et al [2019] regarding ERT appear to apply to Revcovi[®] when used according to the Revcovi[®] package insert.

Prior to initiation of ERT, baseline levels of ADA (i.e., ADA1) catalytic activity and total deoxyadenosine nucleotides (dAXP) in red blood cells should be determined. (Note: Prior to replacement therapy with PEGylated ADA, ADA catalytic activity in plasma is negligible in individuals with ADA-SCID as well as in controls).

The starting dose of Revcovi[®] recommended in the package insert is 0.4 mg/kg (based on ideal body weight) divided into two intramuscular injections of 0.2 mg/kg per week. Following an intramuscular injection, Revcovi[®] is absorbed and circulates in plasma but does not enter cells. At the recommended dose of Revcovi[®], ADA catalytic activity in plasma increases approximately 100-fold, a level at which all the deoxyadenosine (dAdo) produced daily from DNA breakdown is deaminated. As a result, dAdo does not enter the cells of the ADA-deficient individual and, thus, does not undergo phosphorylation to dAXP, which prevents expansion of the intracellular pool of dAXP, the major metabolic cause of the profound lymphopenia present in neonates with ADA-SCID.

Biochemical monitoring of ERT, beginning about two weeks after the first dose of Revcovi[®], involves measuring (1) trough (i.e., pre-injection) level of ADA catalytic activity in plasma, which is due entirely to Revcovi[®], and (2) dAXP levels in red blood cells. These measurements should be repeated at two- to four-week intervals. While the dAXP levels in red blood cells will begin to decline with the initiation of ERT, it usually requires six to eight

weeks for dAXP to fully disappear. Thereafter, sustained normalization of dAXP levels in red blood cells is a useful marker of metabolic correction, and frequency of monitoring can be reduced at the provider's discretion.

It is recommended that ERT be continued for a minimum of 12 to 24 weeks until immune reconstitution is achieved. If lymphocyte counts and in vitro function are satisfactory and clinical status is stable, the dose of Revcovi® may then be consolidated and given once weekly in order to maintain (1) trough (pre-injection) ADA catalytic activity in plasma above 30 mmol/hr/L, and (2) dAXP level in packed red blood cells below 0.02 mmol/L. Although maintaining these two conditions is necessary, in some individuals it may not be sufficient to sustain protective immune function.

In addition to permitting immune reconstitution, ERT has been associated with resolution of hepatocellular abnormalities, pulmonary alveolar proteinosis, and skeletal dysplasia; however, to date this has not been studied systematically. Additionally, in some individuals the neurologic/behavioral abnormalities associated with ADA deficiency have improved; however, it is uncertain if ERT can reverse or prevent these complications.

ERT should be provided continuously until an affected individual is able to undergo definitive therapy with HSCT or HSC-GT, ideally within two years of diagnosis. Of note, the optimal time to discontinue ERT before HSCT or HSC-GT has not been systematically studied; however, in recent years, ERT has been discontinued at the time of HSCT or up to a month after HSCT or HSC-GT.

Between 1990 and 2019, when Revcovi® (PEGylated recombinant bovine ADA) became available, ERT for ADA deficiency was performed with Adagen® (PEGylated purified bovine ADA). Adagen® was used as a long-term therapy in individuals who lacked a suitable HSC donor or were not considered to be candidates for HSCT, or when HSC-GT was unavailable. Some individuals received ERT with Adagen® and did well clinically for up to three decades. However, a gradual decline in lymphocyte counts and immune function occurred in a number of individuals treated with Adagen® for more than five to eight years, resulting in increased frequency of infection and risk of malignancy (lymphoma, hepatic) [Kohn et al 2019]. Because of this experience with Adagen®, long-term maintenance therapy with Revcovi® is not recommended.

Allogeneic Hematopoietic Stem Cell Transplantation (HSCT)

Bone marrow / stem cell transplantation from an HLA-identical healthy sib is the method of choice for treating all forms of SCID. Matched familial donors also have good clinical outcomes.

- Once the diagnosis of ADA-SCID is verified, HLA (human leukocyte antigen) typing of the affected individual, sibs, and parents should be performed.
- HSCT can be performed without cytoreductive conditioning of the affected individual and without depletion of donor T cells.
- Results vary among transplant centers, but the procedure is curative in 70% or more of affected individuals.
- The main risks are graft-vs-host disease and delayed or incomplete recovery of humoral immune function that requires continued immunoglobulin replacement therapy.

Bone marrow / stem cell transplant from a "non-ideal" donor can be considered for the majority of individuals with ADA-SCID who lack an HLA-identical related donor. However, this has the least favorable clinical outcomes regarding sustained immunity and survival [Gaspar et al 2009, Gaspar 2010, Candotti et al 2012, Baffelli et al 2015].

- Among alternative donors, HLA-matched unrelated donors historically have provided better outcomes than haploidentical HSCT.
- Adult bone marrow or peripheral blood stem cells are preferred over umbilical cord blood.

- Donor-derived T cells are depleted to minimize the risk of graft-vs-host disease.
- Pre-transplant cytoreductive "conditioning" of the individual with *ADA*-SCID is often performed to prevent graft loss, which occurs with relative frequency in those with *ADA*-SCID who are not conditioned. The intensity of conditioning is not known.

Note: Some transplant centers do not perform conditioning of the recipient prior to a haploidentical transplant because of the risk of peri-transplant morbidity [Buckley et al 1999]. However, this latter approach has frequently been associated with a failure to achieve stable engraftment [Gaspar et al 2009, Gaspar 2010, Hassan et al 2012].

- Following a T cell-depleted transplant, return of functional T cells requires three to four months. B cell reconstitution is delayed longer or may not be adequately achieved, requiring long-term immunoglobulin replacement therapy.
- Sequence-based HLA typing, improved methods for graft engineering, and post-transplant cyclophosphamide for depletion of alloreactive donor T cells may improve outcomes.
- Graft failures may occur, resulting in restarting ERT while a second allogeneic HSCT or HSC-GT are being considered.

Note: Universal agreement regarding the best methods for performing partially mismatched HSCT/HSC-GT does not exist [Cancrini et al 2010, Gaspar 2010, Hassan et al 2012]. Therefore, when considering therapeutic options, it is important for parents to obtain specific information about prior experience and long-term results of transplants for *ADA*-SCID at the center treating their child.

Autologous Hematopoietic Stem Cell *ADA* Gene Therapy

Gene therapy (HSC-GT). Gene therapy employing autologous CD34⁺ cells transduced with a gammaretroviral vector containing the human *ADA* cDNA (Strimvelis[®]), when used after busulfan pre-conditioning, was shown to be effective in maintaining multilineage *ADA* gene-corrected hematopoietic cells [Aiuti et al 2017, Kohn et al 2019, Reinhardt et al 2021]. Strimvelis[®] was approved in 2016 by the European Medicines Agency. However, it has not become widely available and at present may only be employed as a treatment for *ADA*-SCID at San Raffaele Hospital in Milan, Italy [Cicalese et al 2016, Tucci et al 2022, Grunebaum et al 2023]. See Therapies Under Investigation for other gene therapies not yet approved by a regulatory agency.

Surveillance

Response to targeted therapy. To monitor the individual's response to targeted treatment, the following evaluations are recommended.

- **Immune function.** Frequent evaluation of lymphocyte counts, serum immunoglobulin levels, and various in vitro tests of cellular and humoral immune function should be performed during ERT and following allogeneic HSCT and HSC-GT [Gaspar et al 2009, Kohn et al 2019].
- **Biochemical monitoring.** If the individual continues to receive ERT for more than one year, periodic monitoring of plasma *ADA* activity (due to Revco[®]) and red blood cell dAXP levels should be performed. The monitoring interval may be extended to every three to four months in the second year of treatment, and twice yearly thereafter [Kohn et al 2019].

Occasional monitoring of red blood cell *ADA* activity and dAXP levels may also be performed in individuals who have discontinued ERT to undergo HSCT or HSC-GT. This biochemical monitoring is not a substitute for evaluation of parameters of immune function. But when the results of biochemical monitoring are followed serially and compared with values prior to transplant or gene therapy, this

information may provide an indication of the persistence of engraftment of donor or gene-corrected cells. Biochemical monitoring is usually initiated about six months after the transplant or gene therapy and repeated at one year, and yearly or less frequently thereafter, depending on clinical circumstances.

Approximately 3%-5% of individuals receiving ERT with Adagen® developed neutralizing antibodies, which in several individuals appeared during the first year of treatment following the restoration of T and B cell function. Most individuals in whom this occurred had biallelic *ADA* pathogenic missense variants associated with delayed-onset *ADA*-CID (see Genotype-Phenotype Correlations). The appearance of neutralizing antibodies to Adagen® was associated with a significant decline in levels of *ADA* catalytic activity in plasma, accompanied by a rise in dAXP levels in red blood cells and a subsequent decline in immunologic function.

As Revcovi® was only introduced in 2019, it is unknown whether and how frequently neutralizing antibodies will develop in treated individuals. If levels of *ADA* catalytic activity in plasma decline unexpectedly, particularly in association with a significant increase in dAXP levels in red blood cells, neutralizing antibodies to PEGylated *ADA* should be suspected. Conversely, neutralizing antibodies are very unlikely in the setting of stable levels of *ADA* catalytic activity in plasma and sustained normalization of dAXP levels in red blood cells.

Other. Screening for Epstein-Bar virus (EBV)-related or other lymphoma after age three years is recommended, particularly when lymphocyte counts are declining while on prolonged ERT [Migliavacca et al 2018, Kohn et al 2019, Grunebaum et al 2020].

Agents/Circumstances to Avoid

To ensure the safety of the infant or older individual with *ADA*-SCID or *ADA*-CID pending definitive treatment to achieve immunocompetence, parents and other care providers need to avoid the following:

- Breastfeeding and breast milk, until maternal cytomegalovirus (CMV) status is established by CMV serologies. CMV is a chronic infection, and intermittent viral shedding in various bodily fluids occurs unpredictably. If maternal CMV serology is negative, breast milk may be considered safe for feeding.
Note: Use of pasteurized breast milk while the infant is being prepared for HSCT remains controversial given the severe negative effects of CMV infection in the outcome of HSCT.
- Exposure to young children, sick contacts, or individuals with cold sores in order to decrease the risk of transmission of disease to the infant
- Crowded enclosed spaces due to risk of infectious exposure
- Live viral vaccines for the infant as well as household contacts until after immunocompetence is restored following HSCT
- Transfusion of non-irradiated blood products [Dorsey et al 2017]. Use of only leukoreduced and CMV-negative, irradiated blood products is recommended.
- Areas of construction or soil manipulation, as they increase the risk for fungal exposure

Adenine arabinoside, a substrate for *ADA*, should be avoided as an antiviral agent and/or as chemotherapy of malignancies.

Pentostatin, a potent *ADA* inhibitor used to treat some lymphoid malignancies, would be ineffective in persons with *ADA* deficiency and would interfere with PEGylated *ADA* ERT.

Evaluation of Relatives at Risk

At-risk fetus. When the *ADA* pathogenic variants causing *ADA*-SCID in the family are known, prenatal testing of at-risk fetuses may be performed to help prepare for optimal management of an affected infant at birth, such as identification of a center with expertise in SCID treatment protocols (see Targeted Therapy) that can help initiate the search for an HSCT donor and explain ways to ensure the safety of the infant while awaiting HSCT (see Agents/Circumstances to Avoid).

At-risk newborn. If prenatal testing has not been performed, an at-risk newborn should immediately be placed in an appropriate environment (see Agents/Circumstances to Avoid) and tested for the familial *ADA* pathogenic variants and *ADA* catalytic activity in red blood cells to allow the earliest possible diagnosis and treatment.

See Genetic Counseling for issues related to testing of at-risk relatives for genetic counseling purposes.

Therapies Under Investigation

Hematopoietic stem cell gene therapy (HSC-GT). An experimental approach to HSC-GT for *ADA*-SCID employing a self-inactivating lentiviral vector has been investigated at the University of California, Los Angeles, and Great Ormond Street Hospital, London. Several studies ([NCT01852071](#), [NCT02999984](#), [NCT01380990](#)) have demonstrated safety and efficacy, and no leukemic transformations have been described in *ADA* HSC-GT recipients treated with lentiviral vectors. This approach has resulted in survival and safety comparable to that of HSCT [Kohn et al 2021, Reinhardt et al 2021, Cuvelier et al 2022]. Investigation of this promising form of gene therapy was interrupted by the COVID-19 pandemic and other factors [Grunebaum et al 2023], but a new study at the University of California, Los Angeles, is under way ([NCT05432310](#)).

Looking at data on HSC-GT using either a gammaretroviral vector (see Targeted Therapies) or a lentiviral vector:

- More than 100 individuals with *ADA*-SCID have been treated with HSC-GT using either a gammaretroviral or lentiviral vector.
- Most of these individuals were treated with ERT for three to six months prior to HSC-GT to achieve adequate metabolic detoxification.
- Busulfan pre-conditioning has improved clinical outcomes [Bradford et al 2020, Reinhardt et al 2021].
- 10%-20% of individuals receiving HSC-GT have restarted ERT or received a subsequent HSCT or HSC-GT; the other 80%-90% have normal lymphocyte subsets and are able to discontinue intravenous immunoglobulin [Reinhardt et al 2021].
- In contrast to the experience with gammaretroviral gene therapy for [X-linked SCID](#), [Wiskott-Aldrich syndrome](#), and [chronic granulomatous disease](#), to date only one individual with *ADA* deficiency has developed leukemia as a result of gammaretroviral vector-associated insertional mutagenesis [Cicalese et al 2016, Pai 2021, Reinhardt et al 2021] (see also [Orchard Therapeutics press release](#)). The mechanistic reason for *ADA*-SCID having less leukemic transformation from gammaretroviral vectors is not well understood.

Promising results from other lentiviral vector-based studies include:

- Several studies ([NCT01852071](#), [NCT02999984](#), [NCT01380990](#)) have demonstrated the safety and efficacy of using the self-inactivated lentiviral vector, for which no leukemic transformations have been described in *ADA* HSC-GT recipients.
- Lentiviral vectors are reported to have more neutral insertional sites with less risk of oncogenesis, shorter transduction time, and higher viral titers [Pai 2021].

Search [ClinicalTrials.gov](#) in the US and [EU Clinical Trials Register](#) in Europe for access to information on clinical studies for a wide range of diseases and conditions.

Genetic Counseling

Genetic counseling is the process of providing individuals and families with information on the nature, mode(s) of inheritance, and implications of genetic disorders to help them make informed medical and personal decisions. The following section deals with genetic risk assessment and the use of family history and genetic testing to clarify genetic status for family members; it is not meant to address all personal, cultural, or ethical issues that may arise or to substitute for consultation with a genetics professional. —ED.

Mode of Inheritance

Adenosine deaminase (ADA) deficiency is inherited in an autosomal recessive manner.

Risk to Family Members

Parents of a proband

- The parents of an affected child are presumed to be heterozygous for an *ADA* pathogenic variant.
- If a molecular diagnosis has been established in the proband, molecular genetic testing is recommended for the parents of the proband to confirm that both parents are heterozygous for an *ADA* pathogenic variant and to allow reliable recurrence risk assessment.
- If a pathogenic variant is detected in only one parent and parental identity testing has confirmed biological maternity and paternity, it is possible that one of the pathogenic variants identified in the proband occurred as a *de novo* event in the proband or as a postzygotic *de novo* event in a mosaic parent [Jónsson et al 2017]. If the proband appears to have homozygous pathogenic variants (i.e., the same two pathogenic variants), additional possibilities to consider include:
 - A single- or multiexon deletion in the proband that was not detected by sequence analysis and resulted in the artifactual appearance of homozygosity;
 - Uniparental isodisomy for the parental chromosome with the pathogenic variant that resulted in homozygosity for the pathogenic variant in the proband.
- Heterozygotes (carriers) are asymptomatic and are not at risk of developing the disorder.

Sibs of a proband

- If both parents are known to be heterozygous for an *ADA* pathogenic variant, each sib of an affected individual has at conception a 25% chance of being affected, a 50% chance of being an asymptomatic carrier, and a 25% chance of inheriting neither of the familial *ADA* pathogenic variants.
- Although a good correlation has been established between the effect of pathogenic variants on *ADA* catalytic activity and both clinical and metabolic phenotype,* variability in disease manifestations may be observed among affected sibs (see Genotype-Phenotype Correlations).

* In individuals with compound heterozygosity for two different *ADA* pathogenic variants, the less severe pathogenic variant determines the severity of illness.

- Heterozygotes (carriers) are asymptomatic and are not at risk of developing the disorder.

Offspring of a proband. Unless an affected individual's reproductive partner also has *ADA* deficiency or is a carrier for an *ADA* pathogenic variant, offspring will be obligate heterozygotes (carriers) for a pathogenic variant in *ADA*.

Other family members. Each sib of the proband's parents is at a 50% risk of being a carrier of an *ADA* pathogenic variant.

Carrier Detection

Molecular genetic testing. Molecular genetic carrier testing for at-risk relatives requires prior identification of the *ADA* pathogenic variants in the family.

Biochemical testing. Measurement of ADA enzymatic activity in red blood cells has been used to identify heterozygotes; however, as there is some overlap between the ADA enzymatic activity in red blood cells in heterozygotes and the lower end of the normal range, the results of biochemical testing should be interpreted with caution and confirmed with molecular genetic testing.

Related Genetic Counseling Issues

See Management, Evaluation of Relatives at Risk for information on evaluating at-risk relatives for the purpose of early diagnosis and treatment.

Family planning

- The optimal time for determination of genetic risk and discussion of the availability of prenatal/preimplantation genetic testing is before pregnancy.
- It is appropriate to offer genetic counseling (including discussion of potential risks to offspring and reproductive options) to young adults who are affected, are carriers, or are at risk of being carriers.
- Carrier testing for the reproductive partners of individuals known to be heterozygous for an *ADA* pathogenic variant and for the reproductive partners of individuals affected with ADA deficiency should be considered, particularly if both partners are of the same ancestral background. Prevalence is higher in individuals of Amish, Canadian Mennonite, Inuit, and Somali descent due to founder pathogenic variants in these populations (see Table 5).

Prenatal Testing and Preimplantation Genetic Testing

Molecular genetic testing. Once the *ADA* pathogenic variants have been identified in an affected family member, prenatal and preimplantation genetic testing for ADA deficiency are possible.

Biochemical testing. Prenatal diagnosis for pregnancies at increased risk has been performed by measuring ADA catalytic activity in cultured amniotic fibroblasts or cultured chorionic villi cells grown from fetal cells obtained by amniocentesis or chorionic villus sampling. However, this testing has not been performed in recent years as molecular genetic testing has become widely available.

Differences in perspective may exist among medical professionals and within families regarding the use of prenatal testing. While most centers would consider use of prenatal testing to be a personal decision, discussion of these issues may be helpful.

Resources

GeneReviews staff has selected the following disease-specific and/or umbrella support organizations and/or registries for the benefit of individuals with this disorder and their families. GeneReviews is not responsible for the information provided by other organizations. For information on selection criteria, click [here](#).

- **Immune Deficiency Foundation**
Phone: 800-296-4433
Fax: 410-321-9165
Email: idf@primaryimmune.org
primaryimmune.org

- **ImmUnity Canada**
Canada
Phone: 877-607-2476 (toll-free)
Email: info@immunitycanada.org
immunitycanada.org
- **International Patient Organization for Primary Immunodeficiencies (IPOPI)**
United Kingdom
Phone: +44 01503 250 668
Fax: +44 01503 250 668
Email: info@ipopi.org
ipopi.org
- **Jeffrey Modell Foundation/National Primary Immunodeficiency Resource Center**
Email: info@jmfworld.org
info4pi.org
- **National Human Genome Research Institute (NHGRI)**
[Learning About Severe Combined Immunodeficiency \(SCID\)](#)
- **NCBI Genes and Disease**
[Severe combined immunodeficiency](#)
- **Newborn Screening in Your State**
Health Resources & Services Administration
www.newbornscreening.hrsa.gov/your-state
- **European Society for Immunodeficiencies (ESID) Registry**
Email: esid-registry@uniklinik-freiburg.de
[ESID Registry](#)
- **RDCRN Patient Contact Registry: Primary Immune Deficiency Treatment Consortium**
[Patient Contact Registry](#)
- **United States Immunodeficiency Network (USIDNET) Registry**
Email: contact@usidnet.org
[Enrolling Institutions](#)

Molecular Genetics

Information in the Molecular Genetics and OMIM tables may differ from that elsewhere in the GeneReview: tables may contain more recent information. —ED.

Table A. Adenosine Deaminase Deficiency: Genes and Databases

| Gene | Chromosome Locus | Protein | Locus-Specific Databases | HGMD | ClinVar |
|---------------------|--------------------------|-------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------|---------------------|
| ADA | 20q13.12 | Adenosine deaminase | ADA database ADAbase: Mutation registry for Adenosine Deaminase Deficiency | ADA | ADA |

Data are compiled from the following standard references: gene from [HGNC](#); chromosome locus from [OMIM](#); protein from [UniProt](#). For a description of databases (Locus Specific, HGMD, ClinVar) to which links are provided, click [here](#).

Table B. OMIM Entries for Adenosine Deaminase Deficiency ([View All in OMIM](#))

| | |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| 102700 | SEVERE COMBINED IMMUNODEFICIENCY, AUTOSOMAL RECESSIVE, T CELL-NEGATIVE, B CELL-NEGATIVE, NK CELL-NEGATIVE, DUE TO ADENOSINE DEAMINASE DEFICIENCY |
| 608958 | ADENOSINE DEAMINASE; ADA |

Molecular Pathogenesis

Adenosine deaminase (ADA; also referred to as ADA1), the protein encoded by *ADA*, serves a housekeeping role in the metabolic interconversion of purine nucleosides in all cells. In lymphoid cells ADA serves an essential detoxifying function by eliminating deoxyadenosine (dAdo) in order to prevent deoxyadenosine triphosphate (dATP) pool expansion, which interferes with DNA replication and promotes apoptosis. Although a few *ADA* pathogenic missense variants found in individuals with *ADA*-related severe combined immunodeficiency (SCID) directly alter substrate or zinc cofactor binding, most are distant from the active site and result in very unstable proteins.

Mechanism of disease causation. Loss of *ADA* function (See Genotype-Phenotype Correlations.)

ADA-specific laboratory technical considerations

- Prior to initiation of enzyme replacement therapy (ERT), it is highly recommended to send whole blood in ethylenediaminetetraacetic acid (EDTA) for measuring baseline red blood cell ADA catalytic activity and the concentration of total red blood cell deoxyadenosine nucleotides (dAXP). Levels of red blood cell dAXP correlate with *ADA* pathogenic variants associated with *ADA*-SCID and *ADA*-related combined immunodeficiency (CID) (see Genotype-Phenotype Correlations) and will decrease after initiation of ERT. In some circumstances, this pretreatment biochemical testing can be performed on dried blood spots (DBS, or Guthrie cards) prepared with EDTA anticoagulated blood. Note that measurement of dAXP is performed in the authors' CLIA-certified laboratory, but at present is not otherwise widely available (see Chapter Notes).
- When sending samples for testing of red blood cell ADA catalytic activity and dAXP, it is important to specify whether or not the individual being tested has received a blood transfusion, hematopoietic stem cell transplantation, or gene therapy, since this will confound the interpretation of the test result.
- Novel *ADA* variants of uncertain significance (VUS) predicted to cause single amino acid substitutions or in-frame deletions may be further investigated by functional testing to determine their effect on ADA catalytic activity in a strain of *E. coli* from which the bacterial gene *ada* has been deleted [Arredondo-Vega et al 1998, Hershfield 2003]. However, this analysis is for research purposes and is not certified for clinical testing.

Table 5. *ADA* Pathogenic Variants Referenced in This GeneReview

| Reference Sequences | DNA Nucleotide Change | Predicted Protein Change | Comment [Reference] |
|------------------------------------------------------------|-----------------------|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| NM_000022.4 NP_000013.2 | c.7C>T | p.Gln3Ter | Founder pathogenic variant in persons of Somali ancestry [Sanchez et al 2007] |
| | c.424C>T | p.Arg142Ter | Founder pathogenic variant in persons of Canadian Mennonite ancestry [Santisteban et al 1995] |
| | c.646G>A | p.Gly216Arg | Founder pathogenic variant in persons of Amish ancestry from Juniata & Mifflin County, Pennsylvania [Hirschhorn et al 1991, Strauss & Puffenberger 2009] |

Variants listed in the table have been provided by the authors. *GeneReviews* staff have not independently verified the classification of variants.

GeneReviews follows the standard naming conventions of the Human Genome Variation Society (varnomen.hgvs.org). See [Quick Reference](#) for an explanation of nomenclature.

Chapter Notes

Author Notes

Purine Metabolic and Immunodeficiency Lab [GTR web page](#)

Michael Hershfield [web page](#)

Teresa Tarrant [web page](#)

Acknowledgments

The authors would like to acknowledge the individuals with ADA deficiency and their families who have participated in research and clinical studies; the many clinicians who have cared for individuals with ADA deficiency and have collaborated in studies of the disorder; and the advocacy work of the Immune Deficiency Foundation. Funding support has been from Lediart, Chiesi, and the National Institutes of Health.

Revision History

- 7 March 2024 (bp) Comprehensive update posted live
- 16 March 2017 (ma) Comprehensive update posted live
- 19 June 2014 (me) Comprehensive update posted live
- 22 December 2011 (me) Comprehensive update posted live
- 28 April 2009 (et) Comprehensive update posted live
- 3 October 2006 (me) Review posted live
- 24 April 2006 (mh) Original submission

References

Published Guidelines / Consensus Statements

Gaspar HB, Aiuti A, Porta F, Candotti F, Hershfield MS, Notarangelo LD. How I treat ADA deficiency. *Blood*. 2009;114:3524-32.

Grunebaum E, Booth C, Cuvelier GDE, Loves R, Aiuti A, Kohn DB. Updated management guidelines for adenosine deaminase deficiency. *J Allergy Clin Immunol Pract*. 2023;11:1665-75.

Kohn DB, Hershfield MS, Puck JM, Aiuti A, Blincoe A, Gaspar HB, Notarangelo LD, Grunebaum E. Consensus approach for the management of severe combined immune deficiency caused by adenosine deaminase deficiency. *J Allergy Clin Immunol*. 2019;143:852-63.

Literature Cited

- Aiuti A, Roncarolo MG, Naldini L. Gene therapy for ADA-SCID, the first marketing approval of an ex vivo gene therapy in Europe: paving the road for the next generation of advanced therapy medicinal products. *EMBO Mol Med*. 2017;9:737-40. PubMed PMID: 28396566.
- Albuquerque W, Gaspar HB. Bilateral sensorineural deafness in adenosine deaminase-deficient severe combined immunodeficiency. *J Pediatr*. 2004;144:278–80. PubMed PMID: 14760277.
- Antony FC, Webster AD, Bain MD, Harland CC. Recalcitrant palmoplantar warts associated with adult-onset adenosine deaminase deficiency. *Br J Dermatol*. 2002;147:182–3. PubMed PMID: 12100213.

- Ariga T, Kondoh T, Yamaguchi K, Yamada M, Sasaki S, Nelson DL, Ikeda H, Kobayashi K, Moriuchi H, Sakiyama Y. Spontaneous in vivo reversion of an inherited mutation in the Wiskott-Aldrich syndrome. *J Immunol.* 2001a;166:5245–9. PubMed PMID: 11290809.
- Arredondo-Vega FX, Santisteban I, Daniels S, Toutain S, Hershfield MS. Adenosine deaminase deficiency: genotype-phenotype correlations based on expressed activity of 29 mutant alleles. *Am J Hum Genet.* 1998;63:1049–59. PubMed PMID: 9758612.
- Arredondo-Vega FX, Santisteban I, Richard E, Bali P, Koleilat M, Loubser M, Al-Ghonaïum A, Al-Helali M, Hershfield MS. Adenosine deaminase deficiency with mosaicism for a "second-site suppressor" of a splicing mutation: decline in revertant T lymphocytes during enzyme replacement therapy. *Blood.* 2002;99:1005–13. PubMed PMID: 11807006.
- Artac H, Göktürk B, Bozdemir SE, Toy H, van der Burg M, Santisteban I, Hershfield M, Reisli I. Late-onset adenosine deaminase deficiency presenting with Heck's disease. *Eur J Pediatr.* 2010;169:1033–6. PubMed PMID: 20039061.
- Azzari C, la Marca G, Resti M. Neonatal screening for severe combined immunodeficiency caused by an adenosine deaminase defect: a reliable and inexpensive method using tandem mass spectrometry. *J Allergy Clin Immunol.* 2011;127:1394–9. PubMed PMID: 21624616.
- Baffelli R, Notarangelo LD, Imberti L, Hershfield MS, Serana F, Santisteban I, Bolda F, Porta F, Lanfranchi A. Diagnosis, treatment and long-term follow up of patients with ADA deficiency: a single-center experience. *J Clin Immunol.* 2015;35:624–37. PubMed PMID: 26376800.
- Biesecker LG, Adam MP, Alkuraya FS, Amemiya AR, Bamshad MJ, Beck AE, Bennett JT, Bird LM, Carey JC, Chung B, Clark RD, Cox TC, Curry C, Dinulos MBP, Dobyns WB, Giampietro PF, Girisha KM, Glass IA, Graham JM Jr, Gripp KW, Haldeman-Englert CR, Hall BD, Innes AM, Kalish JM, Keppler-Noreuil KM, Kosaki K, Kozel BA, Mirzaa GM, Mulvihill JJ, Nowaczyk MJM, Pagon RA, Retterer K, Rope AE, Sanchez-Lara PA, Seaver LH, Shieh JT, Slavotinek AM, Sobering AK, Stevens CA, Stevenson DA, Tan TY, Tan WH, Tsai AC, Weaver DD, Williams MS, Zackai E, Zarate YA. A dyadic approach to the delineation of diagnostic entities in clinical genomics. *Am J Hum Genet.* 2021;108:8-15. PubMed PMID: 33417889.
- Bogdał A, Badeński A, Pac M, Wójcicka A, Badeńska M, Didyk A, Trembecka-Dubiel E, Dąbrowska-Leonik N, Walaszczyk M, Matysiak N, Morawiec-Knysak A, Szczepański T, Szczepańska M. Atypical hemolytic uremic syndrome (aHUS) and adenosine deaminase (ADA)-deficient severe combined immunodeficiency (SCID)-two diseases that exacerbate each other: case report. *Int J Mol Sci.* 2021;22:9479. PubMed PMID: 34502390.
- Bollinger ME, Arredondo-Vega FX, Santisteban I, Schwarz K, Hershfield MS, Lederman HM. Brief report: hepatic dysfunction as a complication of adenosine deaminase deficiency. *N Engl J Med.* 1996;334:1367–71. PubMed PMID: 8614422.
- Booth C, Algar VE, Xu-Bayford J, Fairbanks L, Owens C, Gaspar HB. Non-infectious lung disease in patients with adenosine deaminase deficient severe combined immunodeficiency. *J Clin Immunol.* 2012;32:449–53. PubMed PMID: 22350222.
- Bradford KL, Liu S, Krajcinovic M, Ansari M, Garabedian E, Tse J, Wang X, Shaw KL, Gaspar HB, Candotti F, Kohn DB. Busulfan pharmacokinetics in adenosine deaminase-deficient severe combined immunodeficiency gene therapy. *Biol Blood Marrow Transplant.* 2020;26:1819-27. PubMed PMID: 32653625.
- Buckley RH, Schiff SE, Schiff RI, Markert L, Williams LW, Roberts JL, Myers LA, Ward FE. Hematopoietic stem-cell transplantation for the treatment of severe combined immunodeficiency. *N Engl J Med.* 1999;340:508–16. PubMed PMID: 10021471.
- Cancrini C, Ferrua F, Scarselli A, Brigida I, Romiti ML, Barera G, Finocchi A, Roncarolo MG, Caniglia M, Aiuti A. Role of reduced intensity conditioning in T-cell and B-cell immune reconstitution after HLA-identical bone marrow transplantation in ADA-SCID. *Haematologica.* 2010;95:1778–82. PubMed PMID: 20460637.

- Candotti F, Shaw KL, Muul L, Carbonaro D, Sokolic R, Choi C, Schurman SH, Garabedian E, Kesserwan C, Jagadeesh GJ, Fu PY, Gschwend E, Cooper A, Tisdale JF, Weinberg KI, Crooks GM, Kapoor N, Shah A, Abdel-Azim H, Yu XJ, Smogorzewska M, Wayne AS, Rosenblatt HM, Davis CM, Hanson C, Rishi RG, Wang X, Gjertson D, Yang OO, Balamurugan A, Bauer G, Ireland JA, Engel BC, Podsakoff GM, Hershfield MS, Blaese RM, Parkman R, Kohn DB. Gene therapy for adenosine deaminase-deficient severe combined immune deficiency: clinical comparison of retroviral vectors and treatment plans. *Blood*. 2012;120:3635–46. PubMed PMID: 22968453.
- Cicalese MP, Ferrua F, Castagnaro L, Pajno R, Barzaghi F, Giannelli S, Dionisio F, Brigida I, Bonopane M, Casiraghi M, Tabucchi A, Carlucci F, Grunebaum E, Adeli M, Bredius RG, Puck JM, Stepensky P, Tezcan I, Rolfe K, De Boever E, Reinhardt RR, Appleby J, Ciceri F, Roncarolo MG, Aiuti A. Update on the safety and efficacy of retroviral gene therapy for immunodeficiency due to adenosine deaminase deficiency. *Blood*. 2016;128:45–54. PubMed PMID: 27129325.
- Cuvelier GDE, Logan BR, Prockop SE, Buckley RH, Kuo CY, Griffith LM, Liu X, Yip A, Hershfield MS, Ayoub PG, Moore TB, Dorsey MJ, O'Reilly RJ, Kapoor N, Pai SY, Kapadia M, Ebens CL, Forbes Satter LR, Burroughs LM, Petrovic A, Chellapandian D, Heimall J, Shyr DC, Rayes A, Bednarski JJ, Chandra S, Chandrakasan S, Gillio AP, Madden L, Quigg TC, Caywood EH, Dávila Saldaña BJ, DeSantes K, Eissa H, Goldman FD, Rozmus J, Shah AJ, Vander Lugt MT, Thakar MS, Parrott RE, Martinez C, Leiding JW, Torgerson TR, Pulsipher MA, Notarangelo LD, Cowan MJ, Dvorak CC, Haddad E, Puck JM, Kohn DB. Outcomes following treatment for ADA-deficient severe combined immunodeficiency: a report from the PIDTC. *Blood*. 2022;140:685–705. PubMed PMID: 35671392.
- Dorsey MJ, Dvorak CC, Cowan MJ, Puck JM. Treatment of infants identified as having severe combined immunodeficiency by means of newborn screening. *J Allergy Clin Immunol*. 2017;139:733–42. PubMed PMID: 28270365.
- Dorsey MJ, Rubinstein A, Lehman H, Fausnight T, Wiley JM, Haddad E. PEGylated recombinant adenosine deaminase maintains detoxification and lymphocyte counts in patients with ADA-SCID. *J Clin Immunol*. 2023;43:951–64. PubMed PMID: 36840835.
- Dvorak CC, Cowan MJ, Logan BR, Notarangelo LD, Griffith LM, Puck JM, Kohn DB, Shearer WT, O'Reilly RJ, Fleisher TA, Pai SY, Hanson IC, Pulsipher MA, Fuleihan R, Filipovich A, Goldman F, Kapoor N, Small T, Smith A, Chan KW, Cuvelier G, Heimall J, Knutsen A, Loechele B, Moore T, Buckley RH. The natural history of children with severe combined immunodeficiency: baseline features of the first fifty patients of the primary immune deficiency treatment consortium prospective study 6901. *J Clin Immunol*. 2013;33:1156–64. PubMed PMID: 23818196.
- Dvorak CC, Haddad E, Heimall J, Dunn E, Buckley RH, Kohn DB, Cowan MJ, Pai SY, Griffith LM, Cuvelier GDE, Eissa H, Shah AJ, O'Reilly RJ, Pulsipher MA, Wright NAM, Abraham RS, Satter LF, Notarangelo LD, Puck JM. The diagnosis of severe combined immunodeficiency (SCID): The Primary Immune Deficiency Treatment Consortium (PIDTC) 2022 Definitions. *J Allergy Clin Immunol*. 2023a;151:539–46. PubMed PMID: 36456361.
- Dvorak CC, Haddad E, Heimall J, Dunn E, Cowan MJ, Pai SY, Kapoor N, Satter LF, Buckley RH, O'Reilly RJ, Chandra S, Bednarski JJ, Williams O, Rayes A, Moore TB, Ebens CL, Davila Saldana BJ, Petrovic A, Chellapandian D, Cuvelier GDE, Vander Lugt MT, Caywood EH, Chandrakasan S, Eissa H, Goldman FD, Shereck E, Aquino VM, Desantes KB, Madden LM, Miller HK, Yu L, Broglie L, Gillio A, Shah AJ, Knutsen AP, Andolina JP, Joshi AY, Szabolcs P, Kapadia M, Martinez CA, Parrot RE, Sullivan KE, Prockop SE, Abraham RS, Thakar MS, Leiding JW, Kohn DB, Pulsipher MA, Griffith LM, Notarangelo LD, Puck JM. The diagnosis of severe combined immunodeficiency: implementation of the PIDTC 2022 Definitions. *J Allergy Clin Immunol*. 2023b;151:547–55.e5. PubMed PMID: 36456360.
- Flinn AM, Gennery AR. Adenosine deaminase deficiency: a review. *Orphanet J Rare Dis*. 2018;13:65. PubMed PMID: 29690908.

- Gaspar HB. Bone marrow transplantation and alternatives for adenosine deaminase deficiency. *Immunol Allergy Clin North Am*. 2010;30:221–36. PubMed PMID: 20493398.
- Gaspar HB, Aiuti A, Porta F, Candotti F, Hershfield MS, Notarangelo LD. How I treat ADA deficiency. *Blood*. 2009;114:3524–32. PubMed PMID: 19638621.
- Grunebaum E, Booth C, Cuvelier GDE, Loves R, Aiuti A, Kohn DB. Updated management guidelines for adenosine deaminase deficiency. *J Allergy Clin Immunol Pract*. 2023;11:1665-75. PubMed PMID: 36736952.
- Grunebaum E, Cutz E, Roifman CM. Pulmonary alveolar proteinosis in patients with adenosine deaminase deficiency. *J Allergy Clin Immunol*. 2012;129:1588–93. PubMed PMID: 22409989.
- Grunebaum E, Reid B, Naqvi A, Hershfield MS, Kim VH, Muller MP, Hicks LK, Lee E, Betschel S, Roifman CM. Morbidity in an adenosine deaminase-deficient patient during 27 years of enzyme replacement therapy. *Clin Immunol*. 2020;211:108321. PubMed PMID: 31812707.
- Hartog N, Hershfield M, Michniacki T, Moloney S, Holsworth A, Hurden I, Fredrickson M, Kleyn M, Walkovich K, Secord E. Newborn tandem mass spectroscopy screening for adenosine deaminase deficiency. *Ann Allergy Asthma Immunol*. 2022;129:776-83.e2. PubMed PMID: 35914665.
- Hassan A, Booth C, Brightwell A, Allwood Z, Veys P, Rao K, Höning M, Friedrich W, Gennery A, Slatter M, Bredius R, Finocchi A, Cancrini C, Aiuti A, Porta F, Lanfranchi A, Ridella M, Steward C, Filipovich A, Marsh R, Bordon V, Al-Muhsen S, Al-Mousa H, Alsum Z, Al-Dhekri H, Al Ghonaïum A, Speckmann C, Fischer A, Mahlaoui N, Nichols KE, Grunebaum E, Al Zahrani D, Roifman CM, Boelens J, Davies EG, Cavazzana-Calvo M, Notarangelo L, Gaspar HB; Inborn Errors Working Party of the European Group for Blood and Marrow Transplantation and European Society for Immunodeficiency. Outcome of hematopoietic stem cell transplantation for adenosine deaminase-deficient severe combined immunodeficiency. *Blood*. 2012;120:3615–24. PubMed PMID: 22791287.
- Hershfield MS. Combined immune deficiencies due to purine enzyme defects. In: Stiehm ER, Ochs HD, Winkelstein JA, eds. *Immunologic Disorders in Infants and Children*. Philadelphia, PA: WB Saunders, 2004:480-504.
- Hershfield MS. Genotype is an important determinant of phenotype in adenosine deaminase deficiency. *Curr Opin Immunol*. 2003;15:571-7. PubMed PMID: 14499267.
- Hershfield MS, Mitchell BS. Immunodeficiency diseases caused by adenosine deaminase deficiency and purine nucleoside phosphorylase deficiency. In: Scriver CR, Beaudet AL, Sly WS, et al, eds. *The Metabolic and Molecular Bases of Inherited Disease*. 8th ed. New York: McGraw-Hill; 2001. p. 2585-625.
- Hirschhorn R. Immunodeficiency disease due to deficiency of adenosine deaminase. In: Ochs HD, Smith CIE, Puck JM, eds. *Primary Immunodeficiency Diseases: A Molecular and Genetic Approach*. New York, NY: Oxford University Press; 1999:121-39.
- Hirschhorn R, Chakravarti V, Puck J, Douglas SD. Homozygosity for a newly identified missense mutation in a patient with very severe combined immunodeficiency due to adenosine deaminase deficiency (ADA-SCID). *Am J Hum Genet*. 1991;49:878-85. PubMed PMID: 1680289.
- Hirschhorn R, Yang DR, Israni A, Huie ML, Ownby DR. Somatic mosaicism for a newly identified splice-site mutation in a patient with adenosine deaminase-deficient immunodeficiency and spontaneous clinical recovery. *Am J Hum Genet*. 1994;55:59–68. PubMed PMID: 8023852.
- Hirschhorn R, Yang DR, Puck JM, Huie ML, Jiang CK, Kurlandsky LE. Spontaneous in vivo reversion to normal of an inherited mutation in a patient with adenosine deaminase deficiency. *Nat Genet*. 1996;13:290–5. PubMed PMID: 8673127.
- Höning M, Albert MH, Schulz A, Sparber-Sauer M, Schütz C, Belohradsky B, Güngör T, Rojewski MT, Bode H, Pannicke U, Lippold D, Schwarz K, Debatin KM, Hershfield MS, Friedrich W. Patients with adenosine

deaminase deficiency surviving after hematopoietic stem cell transplantation are at high risk of CNS complications. *Blood*. 2007;109:3595-602. PubMed PMID: 17185467.

Jónsson H, Sulem P, Kehr B, Kristmundsdottir S, Zink F, Hjartarson E, Hardarson MT, Hjorleifsson KE, Eggertsson HP, Gudjonsson SA, Ward LD, Arnadottir GA, Helgason EA, Helgason H, Gylfason A, Jonasdottir A, Jonasdottir A, Rafnar T, Frigge M, Stacey SN, Th Magnusson O, Thorsteinsdottir U, Masson G, Kong A, Halldorsson BV, Helgason A, Gudbjartsson DF, Stefansson K. Parental influence on human germline de novo mutations in 1,548 trios from Iceland. *Nature*. 2017;549: 519-22. PubMed PMID: 28959963.

Kahwash BM, Yonkof JR, Abraham RS, Mustillo PJ, Abu-Arja R, Rangarajan HG, Scherzer R. Delayed-onset ADA1 (ADA) deficiency not detected by TREC screen. *Pediatrics*. 2021;147:e2020005579. PubMed PMID: 33975924.

Kesserwan C, Sokolic R, Cowen EW, Garabedian E, Heselmeyer-Haddad K, Lee CC, Pittaluga S, Ortiz C, Baird K, Lopez-Terrada D, Bridge J, Wayne AS, Candotti F. Multicentric dermatofibrosarcoma protuberans in patients with adenosine deaminase-deficient severe combined immune deficiency. *J Allergy Clin Immunol*. 2012;129:762–769.e1. PubMed PMID: 22153773.

Kim VH, Pham-Huy A, Grunebaum E. Neutropenia among patients with adenosine deaminase deficiency. *J Allergy Clin Immunol*. 2019;143:403-5. PubMed PMID: 29753815.

Kohn DB, Booth C, Shaw KL, Xu-Bayford J, Garabedian E, Trevisan V, Carbonaro-Sarracino DA, Soni K, Terrazas D, Snell K, Ikeda A, Leon-Rico D, Moore TB, Buckland KE, Shah AJ, Gilmour KC, De Oliveira S, Rivat C, Crooks GM, Izotova N, Tse J, Adams S, Shupien S, Ricketts H, Davila A, Uzowuru C, Icreverzi A, Barman P, Campo Fernandez B, Hollis RP, Coronel M, Yu A, Chun KM, Casas CE, Zhang R, Arduini S, Lynn F, Kudari M, Spezzi A, Zahn M, Heimke R, Labik I, Parrott R, Buckley RH, Reeves L, Cornetta K, Sokolic R, Hershfield M, Schmidt M, Candotti F, Malech HL, Thrasher AJ, Gaspar HB. Autologous ex vivo lentiviral gene therapy for adenosine deaminase deficiency. *N Engl J Med*. 2021;384:2002-13. PubMed PMID: 33974366.

Kohn DB, Hershfield MS, Puck JM, Aiuti A, Blincoe A, Gaspar HB, Notarangelo LD, Grunebaum E. Consensus approach for the management of severe combined immune deficiency caused by adenosine deaminase deficiency. *J Allergy Clin Immunol*. 2019;143:852-63. PubMed PMID: 30194989.

Komarow HD, Sokolic R, Hershfield MS, Kohn DB, Young M, Metcalfe DD, Candotti F. Impulse oscillometry identifies peripheral airway dysfunction in children with adenosine deaminase deficiency. *Orphanet J Rare Dis*. 2015;10:159. PubMed PMID: 26682746.

Kuo CY, Garabedian E, Puck J, Cowan MJ, Sullivan KE, Buckley RH, Cunningham-Rundles C, Marsh R, Candotti F, Kohn DB. Adenosine deaminase (ADA)-deficient severe combined immune deficiency (SCID) in the US Immunodeficiency Network (USIDNet) Registry. *J Clin Immunol*. 2020;40:1124-31. PubMed PMID: 32880085.

Kwan A, Abraham RS, Currier R, Brower A, Andruszewski K, Abbott JK, Baker M, Ballow M, Bartoshesky LE, Bonilla FA, Brokopp C, Brooks E, Caggana M, Celestin J, Church JA, Comeau AM, Connelly JA, Cowan MJ, Cunningham-Rundles C, Dasu T, Dave N, De La Morena MT, Duffner U, Fong CT, Forbes L, Freedenberg D, Gelfand EW, Hale JE, Hanson IC, Hay BN, Hu D, Infante A, Johnson D, Kapoor N, Kay DM, Kohn DB, Lee R, Lehman H, Lin Z, Lorey F, Abdel-Mageed A, Manning A, McGhee S, Moore TB, Naides SJ, Notarangelo LD, Orange JS, Pai SY, Porteus M, Rodriguez R, Romberg N, Routes J, Ruehle M, Rubenstein A, Saavedra-Matiz CA, Scott G, Scott PM, Secord E, Seroogy C, Shearer WT, Siegel S, Silvers SK, Stiehm ER, Sugerman RW, Sullivan JL, Tanksley S, Tierce ML 4th, Verbsky J, Vogel B, Walker R, Walkovich K, Walter JE, Wasserman RL, Watson MS, Weinberg GA, Weiner LB, Wood H, Yates AB, Puck JM, Bonagura VR. Newborn screening for severe combined immunodeficiency in 11 screening programs in the United States. *JAMA*. 2014;312:729-38. PubMed PMID: 25138334.

- la Marca G, Canessa C, Giocaliere E, Romano F, Duse M, Malvagia S, Lippi F, Funghini S, Bianchi L, Della Bona ML, Valleriani C, Ombrone D, Moriondo M, Villanelli F, Speckmann C, Adams S, Gaspar BH, Hershfield M, Santisteban I, Fairbanks L, Ragusa G, Resti M, de Martino M, Guerrini R, Azzari C. Tandem mass spectrometry, but not T-cell receptor excision circle analysis, identifies newborns with late-onset adenosine deaminase deficiency. *J Allergy Clin Immunol*. 2013;131:1604–10. PubMed PMID: 23280131.
- Liu P, Santisteban I, Burroughs LM, Ochs HD, Torgerson TR, Hershfield MS, Rawlings DJ, Scharenberg AM. Immunologic reconstitution during PEG-ADA therapy in an unusual mosaic ADA deficient patient. *Clin Immunol*. 2009;130:162–74. PubMed PMID: 18952502.
- Malvagia S, Funghini S, Della Bona M, Ombrone D, Mura M, Damiano R, Ricci S, Cortimiglia M, Azzari C, la Marca G. The successful inclusion of ADA SCID in Tuscany expanded newborn screening program. *Clin Chem Lab Med*. 2021;59:e401-e404. PubMed PMID: 33951760.
- Manson D, Diamond L, Oudjhane K, Hussain FB, Roifman C, Grunebaum E. Characteristic scapular and rib changes on chest radiographs of children with ADA-deficiency SCIDS in the first year of life. *Pediatr Radiol*. 2013;43:589–92. PubMed PMID: 23179487.
- Martín-Nalda A, Rivière JG, Català-Besa M, García-Prat M, Parra-Martínez A, Martínez-Gallo M, Colobran R, Argudo-Ramírez A, Marín-Soria JL, García-Villoria J, Alonso L, Arranz-Amo JA, la Marca G, Soler-Palacín P. Early diagnosis and treatment of purine nucleoside phosphorylase (PNP) deficiency through TREC-based newborn screening. *Int J Neonatal Screen*. 2021;7:62. PubMed PMID: 34698070.
- Migliavacca M, Assanelli A, Ponzoni M, Pajno R, Barzaghi F, Giglio F, Ferrua F, Frittoli M, Brigida I, Dionisio F, Nicoletti R, Casiraghi M, Roncarolo MG, Doglioni C, Peccatori J, Ciceri F, Cicalese MP, Aiuti A. First occurrence of plasmablastic lymphoma in adenosine deaminase-deficient severe combined immunodeficiency disease patient and review of the literature. *Front Immunol*. 2018;9:113. PubMed PMID: 29456531.
- Moncada-Vélez M, Vélez-Ortega A, Orrego J, Santisteban I, Jagadeesh J, Olivares M, Olaya N, Hershfield M, Candotti F, Franco J. Somatic mosaicism caused by monoallelic reversion of a mutation in T cells of a patient with ADA-SCID and the effects of enzyme replacement therapy on the revertant phenotype. *Scand J Immunol*. 2011;74:471–81. PubMed PMID: 21671975.
- Murguia-Favela L, Suresh S, Wright NAM, Alvi S, Tehseen S, Hernandez-Trujillo V, Seroogy CM, Haddad E, Nieves D, Walter JE, Pettiford L, Kamani NR, Keller MD, Pham-Huy A, Grunebaum E. Long-term immune reconstitution in ADA-deficient patients treated with elapegademase: a real-world experience. *J Allergy Clin Immunol Pract*. 2023;11:1725–33. PubMed PMID: 36736953.
- Nikolajeva O, Worth A, Hague R, Martinez-Alier N, Smart J, Adams S, Davies EG, Gaspar HB. Adenosine deaminase deficient severe combined immunodeficiency presenting as atypical haemolytic uraemic syndrome. *J Clin Immunol*. 2015;35:366–72. PubMed PMID: 25875700.
- Nofech-Mozes Y, Blaser SI, Kobayashi J, Grunebaum E, Roifman CM. Neurologic abnormalities in patients with adenosine deaminase deficiency. *Pediatr Neurol*. 2007;37:218–21. PubMed PMID: 17765813.
- Pai SY. Built to last: gene therapy for ADA SCID. *Blood*. 2021;138:1287–8. PubMed PMID: 34647983.
- Reinhardt B, Habib O, Shaw KL, Garabedian E, Carbonaro-Sarracino DA, Terrazas D, Fernandez BC, De Oliveira S, Moore TB, Ikeda AK, Engel BC, Podsakoff GM, Hollis RP, Fernandes A, Jackson C, Shupien S, Mishra S, Davila A, Mottahedeh J, Vitomirov A, Meng W, Rosenfeld AM, Roche AM, Hokama P, Reddy S, Everett J, Wang X, Luning Prak ET, Cornetta K, Hershfield MS, Sokolic R, De Ravin SS, Malech HL, Bushman FD, Candotti F, Kohn DB. Long-term outcomes after gene therapy for adenosine deaminase severe combined immune deficiency. *Blood*. 2021;138:1304–16. PubMed PMID: 33974038.
- Richards S, Aziz N, Bale S, Bick D, Das S, Gastier-Foster J, Grody WW, Hegde M, Lyon E, Spector E, Voelkerding K, Rehm HL; ACMG Laboratory Quality Assurance Committee. Standards and guidelines for the interpretation of sequence variants: a joint consensus recommendation of the American College of

- Medical Genetics and Genomics and the Association for Molecular Pathology. *Genet Med*. 2015;17:405-24. PubMed PMID: 25741868.
- Rogers MH, Lwin R, Fairbanks L, Gerritsen B, Gaspar HB. Cognitive and behavioral abnormalities in adenosine deaminase deficient severe combined immunodeficiency. *J Pediatr*. 2001;139:44–50. PubMed PMID: 11445793.
- Sanchez JJ, Monaghan G, Børsting C, Norbury G, Morling N, Gaspar HB. Carrier frequency of a nonsense mutation in the adenosine deaminase (ADA) gene implies a high incidence of ADA-deficient severe combined immunodeficiency (SCID) in Somalia and a single, common haplotype indicates common ancestry. *Ann Hum Genet*. 2007;71:336-47. PubMed PMID: 17181544.
- Santisteban I, Arredondo-Vega FX, Kelly S, Loubser M, Meydan N, Roifman C, Howell PL, Bowen T, Weinberg KI, Schroeder ML, Hershfield MS. Three new adenosine deaminase mutations that define a splicing enhancer and cause severe and partial phenotypes: implications for evolution of a CpG hotspot and expression of a transduced ADA cDNA. *Hum Mol Genet*. 1995;4:2081–7. PubMed PMID: 8589684.
- Sauer AV, Brigida I, Carriglio N, Aiuti A. Autoimmune dysregulation and purine metabolism in adenosine deaminase deficiency. *Front Immunol*. 2012;3:265. PubMed PMID: 22969765.
- Sauer AV, Hernandez RJ, Fumagalli F, Bianchi V, Poliani PL, Dallatomasina C, Riboni E, Politi LS, Tabucchi A, Carlucci F, Casiraghi M, Carriglio N, Cominelli M, Forcellini CA, Barzaghi F, Ferrua F, Minicucci F, Medaglini S, Leocani L, la Marca G, Notarangelo LD, Azzari C, Comi G, Baldoli C, Canale S, Sessa M, D'Adamo P, Aiuti A. Alterations in the brain adenosine metabolism cause behavioral and neurological impairment in ADA-deficient mice and patients. *Sci Rep*. 2017;7:40136. PubMed PMID: 28074903.
- Schejter YD, Even-Or E, Shadur B, NaserEddin A, Stepensky P, Zaidman I. The broad clinical spectrum and transplant results of PNP deficiency. *J Clin Immunol*. 2020;40:123-30. PubMed PMID: 31707514.
- Shearer WT, Dunn E, Notarangelo LD, Dvorak CC, Puck JM, Logan BR, Griffith LM, Kohn DB, O'Reilly RJ, Fleisher TA, Pai SY, Martinez CA, Buckley RH, Cowan MJ. Establishing diagnostic criteria for severe combined immunodeficiency disease (SCID), leaky SCID, and Omenn syndrome: the Primary Immune Deficiency Treatment Consortium experience. *J Allergy Clin Immunol*. 2014;133:1092–8. PubMed PMID: 24290292.
- Sokolic R, Maric I, Kesserwan C, Garabedian E, Hanson IC, Dodds M, Buckley R, Issekutz AC, Kamani N, Shaw K, Tan B, Bali P, Hershfield MS, Kohn DB, Wayne AS, Candotti F. Myeloid dysplasia and bone marrow hypocellularity in adenosine deaminase-deficient severe combined immune deficiency. *Blood*. 2011;118:2688–94. PubMed PMID: 21725047.
- Speckmann C, Neumann C, Borte S, la Marca G, Sass JO, Wiech E, Fisch P, Schwarz K, Buchholz B, Schlesier M, Felgentreff K, Grimbacher B, Santisteban I, Bali P, Hershfield MS, Ehl S. Delayed-onset adenosine deaminase deficiency: strategies for an early diagnosis. *J Allergy Clin Immunol*. 2012;130:991–4. PubMed PMID: 22578972.
- Stenson PD, Mort M, Ball EV, Chapman M, Evans K, Azevedo L, Hayden M, Heywood S, Millar DS, Phillips AD, Cooper DN. The Human Gene Mutation Database (HGMD®): optimizing its use in a clinical diagnostic or research setting. *Hum Genet*. 2020;139:1197-207. PubMed PMID: 32596782.
- Strauss KA, Puffenberger EG. Genetics, medicine, and the Plain people. *Annu Rev Genomics Hum Genet*. 2009;10:513–36. PubMed PMID: 19630565.
- Tanaka C, Hara T, Suzaki I, Maegaki Y, Takeshita K. Sensorineural deafness in siblings with adenosine deaminase deficiency. *Brain Dev*. 1996;18:304–6. PubMed PMID: 8879650.
- Tucci F, Galimberti S, Naldini L, Valsecchi MG, Aiuti A. A systematic review and meta-analysis of gene therapy with hematopoietic stem and progenitor cells for monogenic disorders. *Nat Commun*. 2022;13:1315. PubMed PMID: 35288539.

- van der Spek J, Groenwold RH, van der Burg M, van Montfrans JM. TREC based newborn screening for severe combined immunodeficiency disease: a systematic review. *J Clin Immunol*. 2015;35:416-30. PubMed PMID: 25893636.
- Verhagen MV, Trevisan V, Adu J, Owens CM, Booth C, Calder A. Chest radiographs for distinguishing ADA-SCID from other forms of SCID. *J Clin Immunol*. 2020;40:259-66. PubMed PMID: 31858364.
- Wahjudi TD, Kutzner H, Bleeke M, Hoeger PH. Multicentric dermatofibrosarcoma protuberans in a child with severe combined immunodeficiency due to adenosine deaminase deficiency. *Pediatr Dermatol*. 2021;38:875-8. PubMed PMID: 33931899.
- Whitmore KV, Gaspar HB. Adenosine deaminase deficiency - more than just an immunodeficiency. *Front Immunol*. 2016;7:314. PubMed PMID: 27579027.

License

GeneReviews® chapters are owned by the University of Washington. Permission is hereby granted to reproduce, distribute, and translate copies of content materials for noncommercial research purposes only, provided that (i) credit for source (<http://www.genereviews.org/>) and copyright (© 1993-2024 University of Washington) are included with each copy; (ii) a link to the original material is provided whenever the material is published elsewhere on the Web; and (iii) reproducers, distributors, and/or translators comply with the [GeneReviews® Copyright Notice and Usage Disclaimer](#). No further modifications are allowed. For clarity, excerpts of GeneReviews chapters for use in lab reports and clinic notes are a permitted use.

For more information, see the [GeneReviews® Copyright Notice and Usage Disclaimer](#).

For questions regarding permissions or whether a specified use is allowed, contact: admasst@uw.edu.