Some autoimmune disorders are monogenetic diseases; however, clinical manifestations among individuals vary, despite the presence of identical mutations in the disease-causing gene. In this issue of the JCI, Massaad and colleagues characterized a seemingly monogenic autoimmune disorder in a family that was linked to homozygous loss-of-function mutations in the gene encoding the endonuclease Nei endonuclease VIII-like 3 (NEIL3), which has not been previously associated with autoimmunity. The identification of an unrelated healthy individual with the same homozygous mutation spurred more in-depth analysis of the data and revealed the presence of a second mutation in a known autoimmune-associated gene. Animals lacking Neil3 had no overt phenotype, but were predisposed to autoantibody production and nephritis following exposure to the TLR3 ligand poly(I:C). Together, these results support further evaluation of the drivers of autoimmunity in supposedly monogenic disorders.
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Genetics of immune dysfunction
It is generally recognized that the first primary immunodeficiency was described in 1952, when Ogden Bruton reported a male patient who lacked all serum gammaglobulins (antibodies/immunoglobulins) and suffered from recurrent bacterial infections (1). Remarkably, regular subcutaneous infusion of concentrated human immune serum globulins protected the patient from sepsis (1), demonstrating a link between the absence of gammaglobulin and severe bacterial infections and the possible feasibility of treating such individuals with gammaglobulin replacement therapy. Forty years later, the gene responsible for Bruton’s or X-linked agammaglobulinemia was identified as Btk (Bruton’s tyrosine kinase) (2, 3). Today, with the incredible advances that have been made in next-generation and high-throughout sequencing technologies over the last decade, mutations in more than 300 genes have been discovered that cause primary immunodeficiencies (4). In fact, the clinical manifestations of these conditions would be more appropriately described as immune dysregulation because these conditions often go well beyond susceptibility to infectious diseases and include autoinflammation, autoimmunity, allergic disease, and even malignancy (4, 5).

While these diseases are often considered to be Mendelian and monogenic in nature, the clinical presentation of individuals with diseases that result from mutations in the same gene can be extremely diverse, ranging from mild disease to fatal infections or autoimmunity (4, 6). This variability is also observed in families with the same genetic defect, indicating that disease manifestation is not simply a genotype/phenotype effect. In fact, some mutations remain clinically silent, as evidenced by asymptomatic carriers of ostensibly pathogenic gene mutations (7, 8). This incomplete penetrance of genetic traits is often attributed to environmental or epigenetic influences that modulate the impact of gene mutations on disease pathogenesis (6). However, another possibility is that the condition is actually digenic or multigenic, inasmuch as a mutation in a second gene is required for full-blown clinical disease. This raises the question as to whether a particular disease is monogenic with incomplete penetrance or multigenic in nature. While GWAS studies certainly suggest that many autoimmune diseases are polygenic (9), this hypothesis has rarely been tested in the setting of conditions such as primary immunodeficiencies that are considered to result from mutations in a single gene.

In the past, it has been challenging to formally test the concept that supposed monogenic disorders may instead be polygenetic because, typically, few candidate genes would be analyzed. Moreover, any mutation found in one of the analyzed genes was assumed to be the deleterious genetic lesion — a reasonable conclusion. However, whole-exome and genome sequencing have revealed that mutations are common in the human population and the vast majority of these genetic changes are clinically silent (6). While we tend to focus on a short list of single candidate genes that are likely to be pathogenic, we need to consider the possibility that the disease phenotype may result from genetic epistasis. In this issue, Massaad et al. provide a compelling example whereby immune dysregulation and autoimmunity due to mutation in a disease-associated gene is exacerbated by a mutation in a completely unrelated gene (10).

An asymptomatic individual tells the tale
Massaad et al. describe three siblings from a consanguineous Kuwaiti family suffering from recurrent bacterial and fungal infections, defective peripheral B cell tolerance,
Notably, biallelic, null mutations in LPS-responsive and beige-like anchor) that the three affected siblings characterized and progressive autoimmunity. Thus, contribute to defective immune regulation and autophagy (12, 14–16), all of which would motes immune cell apoptosis, and reduces LRBA deficiency compromises the generation of autoantibodies, and B and T cells exhibited greater apoptosis following activation in vivo and in vitro. Thus, while not directly causing a break in self-tolerance, NEIL3 deficiency appears to predispose to autoimmunity. In NEIL3-deficient mice, further insights in the form of pathogen infection may cause frank autoimmunity. In humans, NEIL3 mutations may exacerbate the immune dysregulation caused by LRBA mutations. It is tempting to speculate that some of the variability in the clinical phenotype of LRBA deficiency, including the identification of asymptomatic individuals (15, 17), could be attributed to the presence or absence of second-hit mutations, such as those reported by Massaad et al. for NEIL3 (10). A major goal for future studies will be to determine whether specific clinical phenotypes result from mutations in NEIL3 or LRBA or whether the combination of defects in both genes underlies disease onset, incidence, and severity.

Concluding remarks
These findings of Massaad et al. are interesting because they illustrate the benign (subclinical) nature of specific gene mutations, yet also reveal potential combinato-rial effects of multiple genetic lesions. This result provides a salient lesson about the need to consider the possible consequences of mutations in unanticipated genes that are observed in essentially all studies employing whole genome sequencing as a platform to discover the molecular cause of human diseases (6). Studies such as that of Massaad et al. will pave the way for the elucidation of additional gene mutations that cooperate to result in clinical phenotypes — and offer a glimpse of the complexity of human genetic diseases that may occasionally be oligogenic, rather than monogenic.

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11. Lee-Kirsch MA, Wolf C, Gunther C, Aicardi-

and severe autoimmunity. This condition was uniformly fatal in the second decade of life. Whole-genome sequencing analysis revealed homozygous mutations in Nei endonuclease VIII-like 3 (NEIL3), which encodes the endonuclease VIII-like enzyme involved in DNA base excision repair, in the three affected individuals. Both parents and all other healthy siblings were heterozygous for this mutation, indicating complete genetic segregation with disease. The specific mutation abolished the enzymatic activity of NEIL3, thereby affecting DNA repair in these individuals and establishing the potential pathogenicity of this genetic lesion. As defects in DNA repair have been associated with human autoimmunity (11), it would not be inappropriate to conclude that deleterious mutations in NEIL3 represent a novel cause of immune dysregulation.

However, Massaad and colleagues also identified the same NEIL3 mutation in a single unrelated healthy adult — a finding that, at face value, disproves the hypothesis that mutations in NEIL3 are disease causing. Despite no presentation of disease, serum from the asymptomatic adult contained high levels of autoantibodies, and B cells from this subject exhibited defects in peripheral tolerance, attributes that were similar to those documented for the three initial cases (10). The paradoxical finding of a healthy carrier with a putative pathogenic homozygous mutation and elevated yet subclinical autoantibody titers led Massaad et al. to reassess the data from their initial whole gene-sequencing analysis of the index patients. This analysis resulted in the identification of a cryptic duplicated homozygous mutation in LRBA (encoding LPS-responsive and beige-like anchor) that results in loss of LRBA protein expression. Notably, biallelic, null mutations in LRBA have been reported by several groups (including authors of the current study) to cause systemic autoimmunity, splenomegaly, recurrent infections, and hypogammaglobulinemia (12–17). At the cellular level, LRBA deficiency compromises the generation and function of regulatory T cells, promotes immune cell apoptosis, and reduces autophagy (12, 14–16), all of which would contribute to defective immune regulation and progressive autoimmunity. Thus, the three affected siblings characterized by Massaad et al. bore homozygous muta-


