single immunization with collagen, with an extremely low incidence (<10%, Fig. 4A) (25). Immunizing CD200<sup>−/−</sup> mice once only (26) resulted in disease onset as early as day 20 and a cumulative incidence of over 50% (Fig. 4A).

That this result was not an artifact of gene targeting was illustrated by infecting C57BL/6<sup>−/−</sup> mice with a replication-deficient adenovirus expressing a soluble Ig fusion protein of CD200R (7, 27). Such mice were highly susceptible to CIA compared with mice receiving a control Ig fusion protein construct (Fig. 4A). Both CD200<sup>−/−</sup> and CD200R-Ig<sub>−/−</sub>-treated animals developed moderate to severe arthritis (6) with synovial inflammation and formation of invasive pannus, resulting in cartilage and bone degradation seen normally only in CIA-susceptible animals (24) (Fig. 4B). Inflammatory cells in the arthritic joints were mainly CD11b<sup>+</sup> cells (20), with a substantial proportion being CD68<sup>+</sup> macrophages (10).

Because EAE and CIA are initiated by activation of self-reactive T lymphocytes (27, 25), enhanced disease could reflect hyperactivation of these cells in the absence of CD200. No evidence for T cell dysregulation in CD200-deficient environments was observed with a range of in vivo and in vitro experiments (10).

Thus, through CD200 expression, diverse tissues regulate macrophages, and probably also granulocytes, directly and continuously through interaction with the inhibitory CD200R (7). The consequences of loss of this pathway can be profound, rendering mice susceptible to tissue-specific autoimmunity and enabling accelerated reactivity of resident tissue macrophages, including those in the CNS. That these effects appear to be unrelated to T cell activation but rather the result of direct deregulation of effector pathways within the macrophage/myeloid lineage has important and broad implications for treatment of neurodegenerative diseases like Alzheimer’s disease or for varied pathologies involving hyperactivation of the myeloid lineage.

References and Notes
10. Supplementary data are available at Science Online at www.sciencemag.org/cgi/content/full/290/5497/1768/DC1.
11. Single- and double-staining procedures were described in (20). Primary antibodies were as in (12), and MOMA-1 (Bachem Bioscience, King of Prussia, PA), rabbit polyclonal anti-DAP12 antibody (15), and anti-CD45 (clone YTS165.1 obtained from S. P. Cobbold, University of Oxford, UK). Secondary antibodies were peroxidase- or alkaline phosphatase–conjugated polyclonal anti-rat or anti-rabbit IgG (Jackson Immunochemicals, NJ). Hind limbs for histological analysis were prepared by means of a procedure adapted from (29).
13. OK90 was prepared by fusing spleenocytes from rats immunized with a mouse CD200−/− rat CD4 fusion protein (6) with the Y3 myeloma, by standard procedures. The monoclonal antibody was selected by its capacity to bind recombinant mCD200−/− rat CD4 in an enzyme-linked immunosorbent assay (ELISA) and to bind those cells predicted to express CD200 (2, 3).
20. R. Hoek et al., data not shown.
23. EAE was induced and scored as described in (10) by subcutaneous immunization with 50 μg of myelin oligodendrocyte glycoprotein (MOG) 35–55 peptide in complete Freund’s adjuvant (CFA), but each mouse received 0.1 mg of H37RA Mycobacterium tuberculosis and intravenous injections of 100 ng of pertussis toxin on the day of immunization and 2 days later.
26. CIA was induced by immunization intradermally with 100 μg of type II collagen in CFA (0.25 mg H37RA M. tuberculosis) and scored only by clinical criteria as described in (24).
27. The adapted mCD200R cDNA (residues 86 to 720) was subcloned in the Xho I site of a modified ATCGT T TAA AC-3

REPORTS

Accumulation of Dietary Cholesterol in Sitosterolemia Caused by Mutations in Adjacent ABC Transporters

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In healthy individuals, acute changes in cholesterol intake produce modest changes in plasma cholesterol levels. A striking exception occurs in sitosterolemia, an autosomal recessive disorder characterized by increased intestinal absorption and decreased biliary excretion of dietary sterols, hypercholesterolemia, and premature coronary atherosclerosis. We identified seven different mutations in two adjacent, oppositely oriented genes that encode new members of the adenosine triphosphate (ATP)–binding cassette (ABC) transporter family [six mutations in ABCG8 and one in ABCG5] in nine patients with sitosterolemia. The two genes are expressed at highest levels in liver and intestine and, in mice, cholesterol feeding up-regulates expressions of both genes. These data suggest that ABCG5 and ABCG8 normally cooperate to limit intestinal absorption and to promote biliary excretion of sterols, and that mutated forms of these transporters predispose to sterol accumulation and atherosclerosis.

In humans, the intestine presents a barrier that prevents the absorption of plant sterols and partially blocks the absorption of cholesterol. This barrier is disrupted in the rare autosomal recessive disorder, sitosterolemia, which is characterized by hyperabsorption of plant ste-
rols such as sitosterol (1–3). Patients with sitosterolemia also hyperabsorb cholesterol and are usually hypercholesterolemic, which leads to the development of xanthomas (cholesterol deposits in skin and tendons) and premature coronary artery disease (2–5). Unlike individuals with other forms of hyperlipidemia, sitosterolemic subjects respond to restriction in dietary cholesterol and to bile acid resin treatment with dramatic reductions in plasma cholesterol levels (2, 3, 6).

Patients with sitosterolemia have markedly elevated (>30-fold) plasma levels of plant sterols (sitosterol, stigmasterol, and campesterol) as well as other neutral sterols with modified side chains (1, 7, 8). Healthy individuals absorb only ~5% of the average 200 to 300 mg of plant sterols consumed each day (9). Almost all of the absorbed sitosterol is quickly secreted into the bile so that only trace amounts of sitosterol and other plant sterols remain in the blood (9). In contrast, subjects with sitosterolemia absorb between 15 and 60% of ingested sitosterol, and they excrete only a fraction into the bile (2–5). The liver secretes sitosterol into the bloodstream, where it is transported as a constituent of low-density and high-density lipoprotein particles (1). With the exception of the brain, the relative proportion of sterol represented by sitosterol in tissues matches that in plasma (10 to 25%) (10). Hyperabsorption and inefficient secretion are not limited to plant steroids. Sitosterolemic subjects absorb a higher fraction of dietary cholesterol than normal subjects, and they secrete less cholesterol into the bile (2–5). Taken together, the genetic and metabolic data indicate that sitosterolemic patients lack a gene product that normally limits the absorption and accelerates the biliary excretion of sterols (2, 3).

The molecular mechanisms that limit sterol absorption are poorly understood, but clues have emerged recently from studies of the orphan nuclear hormone receptor LXR (11, 12). Mice treated with an LXR agonist show a marked decrease in cholesterol absorption and a corresponding increase in the intestinal expression of mRNA encoding the ATP-binding cassette protein–1 (ABCA1), a membrane-associated protein that has been implicated in the transport of cholesterol (11, 13). We hypothesized that sitosterolemic patients might have defects in other genes that limit cholesterol absorption and that the expression of these genes would be regulated by LXR. To test this idea, we used DNA microarrays to search for mRNAs that are induced by the LXR agonist T091317 in mouse liver and intestine (11, 14). A transcript corresponding to a murine EST (AA237916) was induced ~2.5-fold in the livers and intestines of treated mice. This EST resembled three Drosophila genes that encode ABC half-transporters (brown, scarlet, and white) expressed in the pigmentary cells of the eye (15–17). These ABC half-transporters contain six membrane-spanning domains and form two types of heterodimers that transport guanine (brown/white) or tryptophan (scarlet/white). Because a human homolog of white (ABCG1) is implicated in cellular cholesterol efflux from macrophages (18, 19), we reasoned that the LXR-induced protein encoded by AA237916 might be involved in sterol trafficking in liver and intestine, and hence this gene was a candidate for the defect in sitosterolemia.

A full-length cDNA corresponding to

**Fig. 1.** Genomic structure (A), putative topology (B), and predicted amino acid sequences of ABCG5 and ABCG8 (C). ABCG5 and ABCG8 are located on chromosome 2p21 between markers D2S177 and D2S119. (A) ABCG5 and ABCG8 are tandemly arrayed in a head-to-head orientation separated by 374 base pairs. ABCG5 and ABCG8 are both encoded by 13 exons and each spans ~28 kb. (B) The mutations detected in patients with sitosterolemia (Table 1) are indicated on a schematic model of ABCG5 (left) and ABCG8 (right). (C) Predicted amino acid sequence of ABCG5 and ABCG8, which are 651 and 673 residues in length, respectively. Alignment of the inferred amino acid sequences indicates 28% sequence identity and 61% sequence similarity between ABCG5 and ABCG8. Both proteins are predicted to contain six transmembrane segments (22). The putative transmembrane segments of each protein are indicated by blue (ABCG5) or green (ABCG8) cylinders (B) and lines (C). The Walker A and Walker B motifs are highlighted in yellow and lavender, respectively. The ABC signature sequence (C motif) is indicated in purple.

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AA237916 was isolated from a mouse liver cDNA library (OriGene Technologies, Rockville, Maryland), and this sequence was used to identify a human ortholog in the GenBank EST database (T86384). A full-length human sequence was obtained by iterative EST database searches and by cloning from human liver cDNA libraries (OriGene and Clontech, Palo Alto, California). The human cDNA predicts a 651-amino acid protein (Fig. 1C) that shares 80% sequence identity with the mouse sequence (20). Following the standard system of nomenclature in the ABC transporter field, this protein was named ABCG5.

The amino-terminal half of ABCG5 contains the ATP-binding motifs (Walker A and B motifs) and an ABC-transporter signature motif (C motif), and the carboxyl-terminal region is predicted to contain six transmembrane (TM) segments (Fig. 1B) (17, 21, 22). A human EST clone (UniGene T93792) from ABCG5 mapped to chromosome 2p21 between markers D2S177 and D2S119, and the map position was confirmed using a radiation hybrid panel (23). Patel and colleagues previously mapped the human sitosterolemia gene to this same region of chromosome 2 in ten independent sitosterolemia families (24).

The structure of the human ABCG5 gene was characterized by analysis of a bacterial artificial chromosome (BAC) clone that contained the entire gene (Fig. 1A) (25). The gene spans ~28 kb and has 13 exons and 12 introns. The coding sequences and consensus splicing sequences were amplified from genomic DNA by polymerase chain reaction (PCR) and sequenced in nine unrelated subjects with sitosterolemia (Table 1). A sitosterolemia patient from Hong Kong (proband 9) was heterozygous for a transition mutation (CGA to TGA) in codon 408 that introduced a premature stop codon between TM1 and TM2. This mutation was not present in 65 normolipidemic individuals, including 50 Chinese subjects. No other potential disease-causing mutations were identified in ABCG5.

A transversion in codon 604 that substituted a glutamic acid for glutamine (Q604E) in the loop between TM5 and TM6 was found in five sitosterolemia probands but was also present in 23% of the alleles from normolipidemic Caucasians (n = 50).

Genes encoding members of the ABC transporter family are often clustered in the genome (26). Because only a single ABCG5 mutation was identified in our collection of nine sitosterolemia probands, we searched the public and Celera genome sequences for other ABC transporters adjacent to ABCG5. An EST (T84531) that shared weak homology with the Drosophila white gene was identified and expanded using exons predicted by the computer program GENSCAN (27). Eleven of the 13 exons of the new gene, which we name ABCG8, were identified in the databases, and the remaining two exons were identified by sequencing PCR-amplified cDNAs from human hepatic poly(A)⁺ mRNA. ABCG8 shares ~28% amino acid identity with ABCG5 (Fig. 1C). The ABCG8 sequence is most similar to ABCG1, which resembles the Drosophila white gene (16).

The translational start sites of ABCG5 and ABCG8 are estimated by only 374 base pairs, and the two genes contain a translation initiation codon with an upstream in-frame stop codon. The close proximity and opposite orientation of ABCG5 and ABCG8 suggest that the two genes have a bidirectional promoter and share common regulatory elements (28, 29). No obvious LXR response element was identified in the limited amount of sequence available at this time. Other gene pairs with bidirectional promoters form functional complexes (29), as may be the case for ABCG5 and ABCG8.

The predicted intron-exon boundaries of human ABCG8 were confirmed by DNA sequencing. The single-strand conformation polymorphism (SSCP) technique was used to screen the exons and flanking intron sequences of ABCG8 in the nine sitosterolemic patients (Table 1) (30, 31). DNA sequencing of abnormally migrating fragments revealed six different mutations (Table 1 and Fig. 1B). The first patient to be described with sitosterolemia (proband 1) was homozygous for a nonsense mutation (1083G>A) in exon 7 (Fig. 1B) that introduced a premature termination signal codon at codon 361, terminating the protein before TM1. Three other unrelated Caucasian sitosterolemic subjects (proband 3, 5, and 8) were heterozygous for the same mutation (362, 32). One of these probands (proband 5) was originally diagnosed with pseudohomozygous familial hypercholesterolemia (FH), an autosomal recessive disorder characterized by hypercholesterolemia, tendon xanthomas, and exquisite sensitivity to dietary cholesterol (6). Many of the patients originally diagnosed with pseudohomozygous FH were subsequently found to have sito-
terolemia, as was the case with this patient and proband 6 (6, 33). Proband 3 was heterozygous for another nonsense mutation in exon 13 that introduced a stop codon 15 residues from the carboxy terminus of ABCG8. The resulting protein would lack part of TM6 and the short cytoplasmic domain, which contains a cluster of positively charged residues that may be important in positioning these proteins in the membrane (34).

Two missense mutations identified in ABCG8 produced nonconservative amino acid changes at positions that are conserved between the humans and mouse proteins, as well as in ABCG5. One Chinese patient (proband 4) was heterozygous for a missense mutation in exon 6 in codon 263 (Glu for Arg, R263Q). An Amish individual with sitosterolemia was homozygous for a missense mutation (Arg for Gly, G574R) in a residue that is conserved in mouse and human ABCG8. Genomic DNA was available from an additional three of the four living affected family members in this large Amish pedigree (35, 36), and these individuals were homozygous for this same missense mutation (20). A third nonconservative missense mutation was an arginine substitution for a leucine at codon 596. The corresponding sequence in ABCG5 is another nonpolar amino acid, glutamine. None of these three missense mutations were identified in 100 alleles from ethnically matched normolipidemic subjects, which is consistent with their being disease-causing mutations. A common polymorphism (Cys for Tyr, Y54C) with an allele frequency of 23% in control subjects (n = 100 alleles) was also identified in ABCG8.

Thus, we identified two mutant alleles at the ABCG8 locus in four of the nine sitosterolemia patients. Four patients had a single mutant allele in ABCG8, and one patient had a single mutant allele in ABCG5. The identification of multiple different ABCG8 mutations in subjects with sitosterolemia, including nonsense mutations that appear incompatible with protein function, provides strong evidence that sitosterolemia is caused by defects in this gene. It also seems likely that the mutation we found in ABCG5 causes sitosterolemia, although the identification of additional mutations in this gene will be required to substantiate this hypothesis. It remains possible that mutations in another gene (perhaps a different ABC transporter) within the genomic interval mapped by Patel et al. (24) can cause sitosterolemia when present in combination with mutations in ABCG5 or ABCG8.

To determine whether ABCG5 and ABCG8 are regulated coordinately, we examined the tissue distributions of their mRNAs in humans and mice, and their responses to cholesterol feeding in mice. In humans, liver and the small intestine were the major sites of expression of both genes (Fig. 2A). For both ABCG5 and ABCG8, one major transcript of 2.4 kb and 2.6 kb, respectively, but other transcripts were visible by RNA blotting. Additional studies will be required to determine the identity of these transcripts, which presumably result from alternative splicing or differential polyadenylation. In mice, Abcg5 and Abcg8 were expressed at higher levels in the intestine than in the liver, although the relative amounts of expression in these two tissues may be strain specific. Inasmuch as the expression of these two genes is regulated by dietary sterols (see below), definitive studies of tissue expression in humans will require careful control of dietary intake.

If ABCG5 and ABCG8 protect against the accumulation of sterols, then their expression levels would be predicted to increase with cholesterol feeding. To test this hypothesis, we fed mice a high-cholesterol diet (2%), and they were killed after 1, 7, or 14 days. The levels of Abcg5 and Abcg8 mRNAs increased about twofold in intestine and over threefold in liver within 1 week of initiation of the high-cholesterol diet (Fig. 2B). These changes were maintained at 2 weeks (20). As expected, the plasma levels of cholesterol did not significantly change in the cholesterol-fed mice (from 95 mg/dl to 93 mg/dl), because mice rapidly and efficiently convert dietary cholesterol into bile acids and excrete both cholesterol and bile acids into the bile (37). LXR plays a central role in this regulated process by increasing the expression of multiple hepatic genes that promote bile acid synthesis and biliary secretion (12).

The ligands for LXR include hydroxylated sterols that are derived from cholesterol (38, 39). Because ABCG5 is induced by an LXR agonist, it is possible that dietary sterols induce these genes through LXR.

In summary, our data suggest that ABCG5 and ABCG8 are ABC half-transporters that may partner to generate a functional protein. The juxtaposition of the corresponding genes on chromosome 2, the coordinate regulation of their mRNAs in the liver and intestine with cholesterol feeding, and the observation that mutations in either gene are associated with sitosterolemia suggest that these two proteins form a functional complex that mediates efflux of dietary cholesterol from the intestine, and thus protects humans from sterol overaccumulation. This protection is especially important in Western societies that consume high-cholesterol diets. Loss of function of these proteins causes sitosterolemia. Our results raise the possibility that subtle defects in these proteins or in their regulation may underlie the variable responses of healthy individuals to high-cholesterol diets.

Table 1. Molecular defects in nine unrelated individuals with sitosterolemia. Genomic DNA was extracted from cultured fibroblasts or lymphoblasts from the proband or another family member with sitosterolemia (31). All subjects had elevated plasma sitosterol levels (except proband 6 in which plasma sitosterol level was not measured). The age at the time of diagnosis or at the first appearance of xanthomas is provided (when available). The exons and flanking splice site consensus sequences were screened for sequence variations using SSCP and dideoxy-sequencing (31). None of the mutations were found in 100 alleles from normolipidemic controls. The nucleotides are numbered consecutively starting at the A of the initiation codon ATG. Plasma cholesterol levels were obtained from referring physicians or from alleles from normolipidemic controls. The nucleotides are numbered consecutively starting at the A of the initiation codon ATG. Genomic DNA was extracted from cultured fibroblasts or lymphoblasts from the proband or another family member with sitosterolemia (31).

<table>
<thead>
<tr>
<th>Patient (age)</th>
<th>Ethnicity</th>
<th>Mutant alleles</th>
<th>Nucleotide change</th>
<th>Amino acid change(s)</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (8 yr)</td>
<td>German/Scottish</td>
<td>ABCG8 1083G&gt;A</td>
<td>W361Stop</td>
<td>Original case.</td>
<td>G6R</td>
<td>(1)</td>
</tr>
<tr>
<td>2 (13 yr)</td>
<td>Amish</td>
<td>ABCG8 1208G&gt;A</td>
<td>W361Stop</td>
<td>C = 195 mg/dl</td>
<td>(35)</td>
<td></td>
</tr>
<tr>
<td>3 (8 mo)</td>
<td>Caucasian</td>
<td>ABCG8 1083G&gt;A</td>
<td>W361Stop</td>
<td>C fell from 800 to 151</td>
<td>(35)</td>
<td></td>
</tr>
<tr>
<td>4 (4 yr)</td>
<td>Chinese</td>
<td>ABCG8 788G&gt;A</td>
<td>R263Q</td>
<td>C = 556 mg/dl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 (10 yr)</td>
<td>Caucasian</td>
<td>ABCG8 1083G&gt;A</td>
<td>W361Stop</td>
<td>C fell from 375 to 201</td>
<td>(6)</td>
<td></td>
</tr>
<tr>
<td>6 (5 yr)</td>
<td>American</td>
<td>ABCG8 1234C&gt;T</td>
<td>R412Stop</td>
<td>mg/dl on low-chol. diet</td>
<td>(33)</td>
<td></td>
</tr>
<tr>
<td>7 (2 yr)</td>
<td>American</td>
<td>ABCG8 1234C&gt;T</td>
<td>L596R</td>
<td>C fell from 753 to 106</td>
<td>(33)</td>
<td></td>
</tr>
<tr>
<td>8 (3.5 yr)</td>
<td>Chinese</td>
<td>ABCG8 1083G&gt;A</td>
<td>W361Stop</td>
<td>C fell from 718 to 127</td>
<td>(32)</td>
<td></td>
</tr>
<tr>
<td>9 (&lt;10 yr)</td>
<td>Chinese</td>
<td>ABCG8 1222C&gt;T</td>
<td>R408 Stop</td>
<td>C = 620 mg/dl</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note added in proof: After submission of
the manuscript two additional mutations in ABCG5 were identified by sequencing: (i) del547C resulting in a premature stop codon at amino acid 191 in proband 7 and (ii) P231T (691 A→C) resulting in a premature stop codon.

References and Notes
14. Total RNA was prepared from the liver, intestine, and kidney of C57BL/6 mice treated with the LXR agonist T091317 (50 mg/kg). Duplicate RNA samples were labeled with two fluorescent dyes and hybridized to mouse GEM1 microarrays (performed at Incyte Genomics, Palo Alto, CA).
20. K. E. Berge et al., unpublished observations.
23. Chromosomal localization of ABCG5 was confirmed by using probes derived from exon 7 of ABCG5 to amplify a gene-specific fragment from the TNG panel of radiation hybrids from Stanford Human Genome Center (Research Genetics, Inc.). The result was submitted to the RH Server (http://www-shgc.stanford.edu/RH/index.html), which linked ABCG5 to SHGC14952, which is between markers D25S177 and D25S119.
25. The last three exons of ABCG5 were contained in the GenBank sequence entry AC011242 and were further confirmed by PCR analysis from human genomic DNA. The remaining 10 exon/intron boundaries were determined by using PCR and CDNA primers to amplify the exons sequences and the intron/exon boundaries by using genomic DNA and CDNA primers followed by sequence analysis.
27. The 3’ end of ABCG5 was located on BAC RP11-489K22, which had been partially sequenced, but no other ABCB transporters were identified on this BAC. A BAC end sequence in the Genome Survey Sequence database that was located on BAC RP11-489K22 was used to search the Celera Human Fragments database. The public and Celera databases were used to assemble most of the genomic sequences in the region, resulting in the identification of EST T84531, which shared weak homology with the Droso- phila white gene (16). The GENSCAN Web Server (http://genes.mit.edu/GENSCAN.html) was used to identify additional exons within this gene. The sequence of the ~30-kb region was assembled (excluding three gaps) using the Celera Human Fragments database and mouse ESTs in the public database.

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