Identification of Susceptibility Loci for Skin Disease in a Murine Psoriasis Model


*J Immunol* 2006; 177:4612-4619; doi: 10.4049/jimmunol.177.7.4612

http://www.jimmunol.org/content/177/7/4612
Identification of Susceptibility Loci for Skin Disease in a Murine Psoriasis Model

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Psoriasis is a frequently occurring inflammatory skin disease characterized by thickened erythematous skin that is covered with silvery scales. It is a complex genetic disease with both heritable and environmental factors contributing to onset and severity. The CD18 hypomorphic PL/J mouse reveals reduced expression of the common chain of β2 integrins (CD11/CD18) and spontaneously develops a skin disease that closely resembles human psoriasis. In contrast, CD18 hypomorphic C57BL/6J mice do not demonstrate this phenotype. In this study, we have performed a genome-wide scan to identify loci involved in psoriasiform dermatitis under the condition of low CD18 expression. Backcross analysis of a segregating cross between susceptible CD18 hypomorphic PL/J mice and the resistant CD18 hypomorphic C57BL/6J strain was performed. A genome-wide linkage analysis of 94 phenotypically extreme mice of the backcross was undertaken. Thereafter, a complementary analysis of the regions of interest from the genome-wide screen was done using higher marker density and further mice. We found two loci on chromosome 10 that were significantly linked to the disease and interacted in an additive fashion in its development. In addition, a locus on chromosome 6 that promoted earlier onset of the disease was identified in the most severely affected mice. For the first time, we have identified genetic regions associated with psoriasis in a mouse model resembling human psoriasis. The identification of gene regions associated with psoriasis in this mouse model might contribute to the understanding of genetic causes of psoriasis in patients and pathological mechanisms involved in development of disease. The Journal of Immunology, 2006, 177: 4612–4619.
The mouse PL/J strain carrying the CD18 hypomorphic (CD18<sup>hypo</sup>) mutation, with reduced expression of the common chain of β<sub>2</sub> integrins (CD11/CD18) to 2–16% of wild-type levels, develops a skin disease that closely resembles human psoriasis. This disease is characterized by erythema, alopecia, crusts, and scaling as well as abnormal keratinocyte proliferation/differentiation, subcorneal microabscesses, and an increased inflammatory infiltrate in the dermis (33). We earlier reported that CD4<sup>+</sup> T<sub>h</sub>1 cells play a key role in the pathogenesis of the psoriasiform skin disease in this mouse, which was also demonstrated to be dependent on a reduced CD18 gene expression (34). Therefore, this CD18-dependent psoriasis model mimics the autoreactive nature of T cells in psoriasis (34, 35), as do some other models (29, 32).

This psoriasiform skin disease is of particular interest, because it is highly dependent on the genetic background. Namely, the disease develops in CD18<sup>hypo</sup> PL/J mice but not when the same CD18<sup>hypo</sup> mutation is present in C57BL/6J or 129/Sv mice (33, 36). There are no differences in CD18 expression in the three mutant inbred strains carrying the CD18<sup>hypo</sup> mutation (33). This offers the unique possibility to identify genes increasing susceptibility to disease. The polygenic influence on disease development was previously demonstrated in a backcross between the susceptible CD18<sup>hypo</sup> PL/J and the resistant CD18<sup>hypo</sup> C57BL/6J strains ([PL/J × C57BL/6J] × PL/J), where 50% of the mice showed signs of the psoriasiform dermatitis, whereas mice of the (PLJ × C57BL/6J)<sub>F</sub> generation did not develop the psoriasiform skin disease signs (33).

In the present study, we have identified loci determining psoriasis development under the conditions of reduced CD18 expression, using genome-wide linkage analysis of a backcross between the susceptible CD18<sup>hypo</sup> PL/J and the resistant CD18<sup>hypo</sup> C57BL/6J strains. A major locus on chromosome 10, distinct from the CD18 gene, was identified. An additional locus telomeric to the CD18 gene was found on chromosome 10. Furthermore, we identified a locus on chromosome 6 contributing to the most severe form of the psoriasiform dermatitis in this cross. An additional locus was located on chromosome 18. We were also able to demonstrate true epistatic interactions between two distinct loci on chromosomes 1 and 4, respectively. The chromosome 4 locus was detected only after allowing for genetic interaction, demonstrating the complex etiology of this psoriasiform skin disease. In conclusion, we have identified, for the first time, loci playing a role in a murine psoriasis model that strongly resembles human psoriasis.

Materials and Methods
Nature of the targeting mutation
Previously, a construct for homologous recombination in the CD18 gene was prepared by screening a murine genomic DNA library using the mouse cDNA clone 4 as a probe for CD18 gene (1). A single λ clone containing exons 1–3 was isolated and a construct for homologous recombination was prepared as published earlier (38). The construct was used with the intent to produce an insertion mutation duplicating exons 2 and 3 with interruption of one copy of exon 3 with the neomycin resistance cassette. The insertion mutation resulted in a hypomorphic rather than in a null allele due to low expression of a cryptic promoter in the plasmid construct. Homozygous mutant mice have a 2 or 16% of normal CD18 expression on leukocytes in the resting or activated state, respectively.

Mouse
The CD18<sup>hypo</sup> PL/J mice used in the present study were generated by crossing the CD18<sup>hypo</sup> mutation, derived from 129/SvEv background (34), to the PL/J inbred strain, followed by four generations of backcrossing to PL/J (N4). Consequently, −6.25% of the genome still originates from 129/Sv (39). The 129/SvEv-derived fragment surrounding the CD18 gene comprises 71 Mb (36 cM) with the boundary markers D10mit194 to D10mit114. The CD18<sup>hypo</sup> C57BL/6J mice had been backcrossed to C57BL/6J for 10 generations (The Jackson Laboratory), and we therefore considered them to be of a homogeneous C57BL/6J background (39). The 129/SvEv-derived fragment surrounding the CD18 gene was 70 megabase (Mb) (35 centimorgan (cM)) with the boundary markers D10mit38 to D10mit233. To generate the backcross, male CD18<sup>hypo</sup> PL/J mice with a clinical psoriasiform phenotype were selected and crossed with female CD18<sup>hypo</sup> C57BL/6J mice. Female F<sub>1</sub> mice were backcrossed to male CD18<sup>hypo</sup> PL/J. Three hundred and forty-three ([PL/J × C57BL/6J]<sub>F</sub> × PL/J) backcross mice were generated. All mice were kept under specific pathogen-free conditions in compliance with the German Law for Welfare of Laboratory Animals.

Genotyping
DNA was prepared from tail biopsies by an alkaline lysis protocol (40). Briefly, tail biopsies were incubated in 50 mM NaOH at 2 h at 95°C, vortexed, and neutralized in 1 M Tris-HCl, pH 8.0. After centrifugation the supernatant was used for PCR. This was performed with 10 ng of DNA in a reaction volume of 10 μl containing the following: 10 mM Tris-HCl (pH 9.0), 50 mM KCl, 1.5 mM MgCl<sub>2</sub>, 0.3 μM forward and reverse primers (MWG-Biotech and Applied Biosystems), 100 μM dNTP (Amersham Biosciences), and 0.25 U of TaqDNA polymerase (Amersham Biosciences). Forward primers were labeled with fluorescent dyes.

PCR was performed in a thermal cycler (MJ Research) under the following amplification conditions: denaturation at 94°C for 2.5 min, annealing at 56°C for 45 s, polymerization at 72°C for 1 min, followed by 30 cycles of 94°C for 30 s, 56°C for 45 s, and 72°C for 1 min. The final cycle ended by elongation at 72°C for 6 min. PCR products were analyzed on a MegaBACE 1000 (Amersham Biosciences), according to the manufacturer’s protocol.

Selection of markers for genome screen
The parental CD18<sup>hypo</sup> PL/J and CD18<sup>hypo</sup> C57BL/6J strains were screened using 186 microsatellite makers across the genome. For 19 of these markers, alleles from 129/Sv were detected in the CD18<sup>hypo</sup> PL/J parental strain. No 129/Sv alleles were detected in the CD18<sup>hypo</sup> C57BL/6J parental strain. Eighty-three markers with an average marker distance of 17 cM were selected for genome-wide screen (data not shown). Of these markers, 16 identified 129/Sv fragments in the CD18<sup>hypo</sup> PL/J parental strains. The genome-wide screen was performed on 53 mice with the most severe disease and 41 unaffected mice.

For the complementary screen of loci identified in the genome-wide screen, an additional 12 markers were genotyped (data not shown). In total, 343 backcross mice were genotyped in the complementary screen.

Evaluation of the psoriasiform skin disease
The severity of clinical signs in backcross mice was evaluated every 2 wk for up to 20 mo using an adapted psoriasis area and severity index (PSAI) score as used in assessment of the severity of human psoriasis elsewhere (41). For CD18<sup>hypo</sup> mice, the PSAI score was modified accordingly; 0, no signs; 1, erythema of the ears, scaling of the tail; 2, hair loss in addition to the signs for 1; 3, hair loss, isolated or widespread slight scaling; 4, moderate scaling on a large area of the body or strong scaling at a few, small or large regions.

Because distinct components of the disease are influenced by different genetic loci, for each backcross mouse the following phenotypes were determined: 1) maxscore (maximal degree of disease severity) is the highest adapted PSAI score observed for each individual mouse; 2) onset is the week when first signs of the disease appeared; 3) susceptibility for the disease was considered as positive, if the adapted PSAI score was 1 or higher; 4) area under the curve (AUC) (42), as a measurement of the overall severity of the disease, is the accumulated sum of the adapted PSAI scores determined every 2 wk for 34 wk after weaning.

Statistical and linkage analysis
Quantitative trait loci (QTL) linkage analysis was conducted using the R (43) and the R/qtl software (44). Results were obtained under the imputation model (45). The susceptibility, onset, maxscore, and AUC phenotypes were analyzed separately under the assumption of sex as an interactive covariate. For the X chromosome, default procedure in R/qtl is to keep the four genotype groups (males are hemizygous A or B, and females are AB or BB) separate: The “null model” for the X chromosome includes sex as a covariate. To investigate genetic interactions a two-dimensional genome scan with a two-QTL model was performed. The two-QTL model compares a full model in the presence of covariates (y = μ + βq1 + βq2 + βq1q2 + αY + Zq1 + Zq2 + Zq1q2 + e) to a null model (y = μ + αY + e). The epistasis, LOD support interval (LOD<sub>α</sub>), compares the full model to an additive model (y = μ + βq1 + βq2 + αY + Zq1 + Zq2 +
Results

In a backcross between CD18<sup>hypo</sup> PL/J and C57BL/6J mice, 16% of offspring develop a severe psoriasiform phenotype

PL/J mice carrying a hypomorphic mutation in the CD18 gene (CD18<sup>hypo</sup>) developed a psoriasiform dermatitis strongly resembling human psoriasis, whereas CD18<sup>hypo</sup> C57BL/6J mice did not show any signs of this phenotype. (PL/J × C57BL/6J)F<sub>1</sub> mice are not susceptible to this disease, indicating the presence of recessive susceptibility genes. To identify chromosomal regions containing genes involved in the development of the psoriasiform skin disease, (PL/J × C57BL/6J)<sub>F1</sub> × PL/J backcross mice were observed for their psoriasiform phenotype using an adapted PASI score for clinical assessment.

Two hundred and nine of 343 offspring of the backcross generation (61%) did not show any signs of the psoriasiform dermatitis (Table I, maxscore of 0), whereas for 16% (n = 56) a severe phenotype (maxscore of 3 or 4) was observed. The first signs of the psoriasiform skin disease (onset) developed earlier in mice reaching high adapted PASI scores compared with less affected animals. We observed a difference in the susceptibility to the psoriasiform skin disease between males and females. Seventy-three percent of susceptible mice were females (n = 98) with at least twice as many as males for all severity degrees observed in this psoriasiform skin disease of this population. In contrast, within unaffected mice, 60% (n = 126) were males, pointing to a higher susceptibility to the psoriasiform skin disease in female CD18<sup>hypo</sup> mice compared with their male littermates.

Table II. QTL for phenotypes of the psoriasiform skin disease identified in genome screen of CD18<sup>hypo</sup> backcross mice

<table>
<thead>
<tr>
<th>Phenotype</th>
<th>Marker&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Position&lt;sup&gt;b&lt;/sup&gt; (60)</th>
<th>LOD Score&lt;sup&gt;c&lt;/sup&gt; (n = 94)&lt;sup&gt;d&lt;/sup&gt;</th>
<th>LOD Score&lt;sup&gt;c&lt;/sup&gt; (n = 343)&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxscore</td>
<td>D10mit86/D10mit214</td>
<td>19.0</td>
<td>7.7**</td>
<td>9.7**</td>
</tr>
<tr>
<td></td>
<td>D18mit194</td>
<td>22.0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Onset</td>
<td>D10mit236</td>
<td>25.7</td>
<td>2.6*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D6mit67</td>
<td>41.5</td>
<td>4.9**</td>
<td>4.6**</td>
</tr>
<tr>
<td>Susceptibility</td>
<td>D10mit17</td>
<td>106.3</td>
<td>3.1*</td>
<td>1.7*</td>
</tr>
<tr>
<td></td>
<td>D10mit214</td>
<td>19.0</td>
<td>6.9**</td>
<td>10.2**</td>
</tr>
<tr>
<td>AUC</td>
<td>D10mit194</td>
<td>22.0</td>
<td>1.8*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D1mit236</td>
<td>25.7</td>
<td>2.3*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D10mit214</td>
<td>19.0</td>
<td>4.4**</td>
<td>6.7**</td>
</tr>
<tr>
<td></td>
<td>D1mit55</td>
<td>24.0</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D1mit292</td>
<td>107.3</td>
<td>2.3*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D4mit256</td>
<td>82.7</td>
<td>2.1*</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Marker that is closest to the peak LOD score.

<sup>b</sup> Highest LOD score (<i>n</i> = 94) at each chromosomal position.

<sup>c</sup> Marker position in centimorgans according to genetic map (www.informatics.jax.org).

<sup>d</sup> Significance levels: *70% probability of linkage established by permutation tests. Genotype-wide significance applied for the genome screen. Locus-wide significance applied for complementary screen of loci of interest.
The QTLs identified in the genome-wide screen of the first 94 mice are shown in Table II. Highly significant linkage (with a probability of >99%) was found for a locus on chromosome 10 close to the marker D10mit86/D10mit14 (Table II). Notably, this linkage could not be due to the CD18<sup>hypo</sup> mutation itself or the 129/SvEv-originating segment adjacent to the CD18 gene, because both parental strains of the cross carry this region, and thus all mice of the backcross. However, these results distinctly indicate that additional gene(s) on chromosome 10 influence the development of the psoriasiform disease in this cross. The psoriasiform skin disease-promoting alleles in this locus originate from PL/J (Table III).

We identified a locus on chromosome 6 influencing the time point of onset of the disease (Table II and Fig. 1). The peak is located between markers D6mit4 and D6mit25 with the highest logarithm of odds (LOD) score close to marker D6mit67. The disease-promoting allele originates from the PL/J parental strain (Table III). Linkage was indicated for the phenotypes severity (expressed as maxscore) and susceptibility at the same region on chromosome 6 (LOD, 1.4 and 1.6, respectively). In addition, indication of linkage was detected for markers on chromosomes 1, 4, and 18 (Table II) in which the disease-promoting alleles again originate from PL/J (Table III).

**Linkage analysis of all 343 mice strengthens support for the chromosome 10 locus**

As a second step in our mapping approach, we increased the marker density of the chromosome 1, 4, 6, 10, and 18 regions identified in the genome-wide screen and an additional 249 mice were included in the analysis. Linkage analysis was performed on all 343 mice (Table II). The locus on chromosome 10 clearly contributed to the disease in the additional 249 mice as well as the LOD score being increased to a maximum of LOD of 10.2 (Table II). In contrast, the locus on chromosome 6 that was linked to the time point of onset in the analysis of the phenotypic extreme individuals was no longer associated with susceptibility phenotypes. This indicates that the susceptibility allele of the locus on chromosome 6 is present in the most severely affected mice and contributes to that phenotype. However, when adding the rest of the backcross mice in the analysis, this effect was diluted and no longer detectable.

**Chromosome 10 potentially harbors two loci that affect the development of the psoriasiform skin disease in addition to the CD18<sup>hypo</sup> mutation**

Both the parental strains in the present backcross contain the CD18<sup>hypo</sup> mutation on chromosome 10, originally generated in 129/SvEv embryonic stem cells. Therefore, in the present study, all offspring of the backcross mice carry genomic DNA fragments from the 129/SvEv strain that surround the CD18 gene on chromosome 10. For this reason, this part of the genome does not segregate as does the rest of the genome in this backcross, but rather appears as nonpolymorphic in the linkage analysis. Because no recombinations in this fragment were detectable, the genetic distance is estimated to be very short, although the physical distance is 71 Mb. To test whether this may skew the linkage analysis results, a separate analysis was performed to determine the association of individual markers on chromosome 10 with the phenotype maxscore (Table IV). For all seven markers mice with homozygosity for PL/J alleles (B) show a significantly higher maxscore than heterozygous mice (H) with the most prominent difference being for markers D10mit86 and D10mit214 (<i>p</i> < 0.0001).

To circumvent the nonpolymorphic 129/SvEv region and to dissect whether more than one additional locus besides CD18 is present on chromosome 10, linkage analysis was performed after treating it as two chromosomes. Markers D10mit80, D10mit50, D10mit213, D10mit86/D10mit214, D10mit233/D10mit14 and D6mit274, D6mit4, D6mit261, D6mit67/D6mit230, D6mit10, D6mit25, and D6mit14. For markers mentioned at the same genetic position, no recombination was detected between these markers in the cross. Horizontal lines indicate significance levels for linkage with a probability of 95%: maxscore, LOD (0.95) = 3.3; onset, LOD (0.95) = 3.2.

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**Table III. Dominance relationship between PL/J and C57BL/6J alleles at the loci associated with the psoriasiform skin disease**

<table>
<thead>
<tr>
<th>Marker&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Affected&lt;sup&gt;b&lt;/sup&gt; (n = 53)</th>
<th>Unaffected (n = 41)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>D10mit86</td>
<td>42</td>
<td>11</td>
</tr>
<tr>
<td>D10mit233/D10mit14</td>
<td>37/36</td>
<td>16/17</td>
</tr>
<tr>
<td>D6mit67</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>D18mit194</td>
<td>33</td>
<td>20</td>
</tr>
<tr>
<td>D1mit236/D1mcg101</td>
<td>34/33</td>
<td>19/20</td>
</tr>
<tr>
<td>D1mit111/D1mit292</td>
<td>30/32</td>
<td>23/21</td>
</tr>
<tr>
<td>D4mit170</td>
<td>29</td>
<td>24</td>
</tr>
</tbody>
</table>

<sup>a</sup> Markers showing highest LOD scores on the respective chromosome.

<sup>b</sup> Affected, maxscore of 3 or 4; unaffected, maxscore of 0. B, Number of animals homozygous for PL/J alleles; H, heterozygous.

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**FIGURE 1.** LOD score curves representing the phenotypes maxscore (solid line) and onset (dotted line) for chromosomes 6 and 10. Positions of microsatellite markers on chromosomes 10 and 6, respectively, are indicated: D10mit80, D10mit50/D10mit14, D10mit86/D10mit214, D10mit233/D10mit14 and D6mit274, D6mit4, D6mit261, D6mit67/D6mit230, D6mit10, D6mit25, and D6mit14. For markers mentioned at the same genetic position, no recombination was detected between these markers in the cross. Horizontal lines indicate significance levels for linkage with a probability of 95%: maxscore, LOD (0.95) = 3.3; onset, LOD (0.95) = 3.2.
Three additional loci were found to be of significance as indicated by chromosome 1 and 18.

Susceptibility loci for the psoriasiform skin disease on chromosomes 1 and 18

Three additional loci were found to be of significance as indicated by the genome-wide screen of all 343 mice; Two locations on chromosome 1 were significantly linked to disease severity, at D1mit236 (25 cM; 46 Mb) and at D1mit17/D1mit292 (107 cM; 191 Mb). A locus influencing the severity of the disease was identified on chromosome 18, D18mit194/D18mit35 (22–24 cM; 44–46 Mb) (Table II).

Genetic interaction of the locus on chromosome 1 determines the involvement of the chromosome 4 locus in disease severity

The most centromeric of the two loci on chromosome 1 acts in a true epistatic fashion with a locus on chromosome 4, D4mit170 (67 cM) (Fig. 3). The locus on chromosome 4, D4mit308 (57.4 cM), most likely representing the same linked region as D4mit170, was only detected from a suggestive LOD score (LOD, 1.7) for onset in the initial genome-wide screen (Table II).

When applying a two-dimensional screen searching for any pairs of loci affecting the disease in an interactive fashion, we were able to show that the effect of the chromosome 4 locus was only penetrant if the genotype at the centromeric chromosome 1 locus is homozygous for PL/J, and heterozygous at the chromosome 1 locus overcame the effect of the chromosome 4 locus, which is the definition of an epistatic interaction.

Discussion

CD18<sup>hypo</sup> PL/J mice show a psoriasiform skin disease strongly resembling human psoriasis in many aspects of its pathogenesis, thus representing an animal model that may contribute to a better understanding of this condition or other inflammatory skin diseases. The CD18<sup>hypo</sup> mutation perhaps is not the only disease-promoting factor in these mice, because other strains of different genetic backgrounds carrying the same CD18<sup>hypo</sup> mutation do not reveal any signs of this skin disease. Therefore, this polygenic mouse model is particularly suitable for the identification of genes involved in the development of the psoriasiform phenotype, with an impact also for the human disease.

In this study, we performed the first genome-wide linkage analysis in an animal model for psoriasis to search for loci that control clinical manifestations of this inflammatory skin disease. In the CD18<sup>hypo</sup> psoriasiform mouse model, the mutation leading to reduced CD18 expression is known (33). Important modifier loci with dominant protective genes from the C57BL/6J mouse were identified in a backcross between CD18<sup>hypo</sup> mice of the susceptible PL/J and resistant C57BL/6J strains (36).

In addition to the CD18<sup>hypo</sup> mutation, we found that chromosome 10 harbors two loci contributing to the disease (Fig. 4). A locus on chromosome 6 was identified to predominantly influence the time point when the first signs appear, potentially leading to a more severe condition. We also demonstrated an epistatic interaction between a locus on chromosome 1 and one on chromosome 4. The effect of the chromosome 4 locus was only penetrant if the genotype at the chromosome 1 locus was homozygous for PL/J. Consequently, heterozygosity at the chromosome 1 locus overcame the effect of the chromosome 4 locus, which is the definition of an epistatic interaction.

An additional locus on chromosome 1 and one on chromosome 18 were also shown to play a role in the severity of the psoriasiform skin disease.

As observed in an earlier backcross experiment (33), the fact that no psoriasiform phenotype developed in (PL/J × C57BL/6J) F<sub>2</sub> crosses (Fig. 2) with the D10mit86/D10mit214 locus having the strongest impact.

Table IV. Association of single markers on chromosome 10 with the phenotype maxscore

<table>
<thead>
<tr>
<th>Marker</th>
<th>Genetic Position (cM)</th>
<th>Genotype</th>
<th>Backcross Mice (n)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Maxscore&lt;sup&gt;c&lt;/sup&gt;</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>D10mit80</td>
<td>4</td>
<td>B</td>
<td>159</td>
<td>1.1 ± 1.3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>170</td>
<td>0.6 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>D10mit50</td>
<td>7</td>
<td>B</td>
<td>167</td>
<td>1.1 ± 1.3</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>175</td>
<td>0.5 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>D10mit213</td>
<td>11</td>
<td>B</td>
<td>163</td>
<td>1.1 ± 1.3</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>179</td>
<td>0.5 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>D10mit86</td>
<td>17</td>
<td>B</td>
<td>151</td>
<td>1.3 ± 1.4</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>161</td>
<td>0.4 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>D10mit214</td>
<td>19</td>
<td>B</td>
<td>169</td>
<td>1.2 ± 1.4</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>172</td>
<td>0.4 ± 0.9</td>
<td></td>
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<tr>
<td>D10mit233</td>
<td>62</td>
<td>B</td>
<td>81</td>
<td>1.6 ± 1.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>169</td>
<td>0.6 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>D10mit14</td>
<td>65</td>
<td>B</td>
<td>119</td>
<td>1.2 ± 1.4</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>172</td>
<td>0.6 ± 1.1</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> B, Number of animals homozygous for PL/J alleles; H, heterozygous.
<sup>b</sup> Number of backcross mice genotyped for each marker.
<sup>c</sup> The mean of the highest adapted PASI scores from the mice in each group.
<sup>d</sup> SD.

Table V. Linkage of markers on the proximal and distal part of chromosome 10 with phenotypes of the psoriasiform skin disease after dividing chromosome 10 into two chromosomes

<table>
<thead>
<tr>
<th>Phenotype</th>
<th>Maxscore</th>
<th>Onset</th>
<th>Susceptibility</th>
<th>AUC</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>D10mit86/D10mit214&lt;sup&gt;a&lt;/sup&gt; (17–19 cM)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.6&lt;sup&gt;c&lt;/sup&gt; (70; 95; 99%)</td>
<td>4.6</td>
<td>10.2</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>D10mit233/D10mit14&lt;sup&gt;a&lt;/sup&gt; (62–65 cM)</td>
<td>4.6 (1.8; 2.5; 3.3)</td>
<td>1.0 (1.7; 2.5; 3.0)</td>
<td>4.3</td>
<td>4.0 (1.7; 2.5; 3.1)</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

<sup>a</sup> Markers on the proximal (D10mit86/D10mit214) and distal part (D10mit233/ D10mit14) of chromosome 10.
<sup>b</sup> Marker position on chromosome 10.
<sup>c</sup> LOD score.
<sup>d</sup> Significance levels for 70, 95, and 99% probability of linkage established by permutation tests.
used. In the previous study, the CD18hypo mutation had been back-
pressed C57BL/6J inheritance. However, compared with 50% in-
incidence of psoriasiform skin disease in these mice were 100% (33). However, it was determined in the screen of the parental strains, before the genome screen, that all the 129/Sv impurity originated from the PL/J parentage. The impurity of the genomic DNA fragments on chromosome 10 surrounding the CD18<sup>hypo</sup> mutation still originating from 129/SvEv in the present cross was 71 Mb (36 cM) long between markers D10mit194 (29 cM) and D10mit14 (65 cM). Consequently, because both parental strains used for generating the backcross animals carried this section of chromosome 10, all of their offspring carried a 129/SvEv-derived fragment in that region. For genetic analysis, this results in a fragment of chromosome 10 that is non-polymorphic in the cross and hence did not contribute to any linkage information. However, this did not skew the linkage analyses results, because LOD scores for chromosomal regions on both sides of the inserted region could be confirmed, when determining association of individual markers or performing linkage analysis after division of chromosome 10 into two chromosomes. These results suggest that, in addition to the region around marker D10mit214, which shows the highest LOD scores, a second gene locus on chromosome 10 around markers D10mit233 and D10mit14 might be linked with the psoriasiform skin disease.

The observation that the PL/J susceptible genetic influence is mainly recessive (33) suggested that, in the present cross, loci could be expected with a dominant protective effect inherited from C57BL/6J. In fact, all loci with linkage or suggestive linkage to the psoriasiform skin disease confirmed this expectation. However, it is not possible to conclude whether the PL/J alleles are recessive or codominant compared with the C57BL/6J alleles, because a backcross cannot differentiate between heterozygotes and homozygotes for the C57BL/6J allele. An intercross would be more appropriate because in the F<sub>2</sub> generation homozygosity for the C57BL/6J allele also appears and, furthermore, could provide additional linkage data because in complex disorders the genetic context is decisive for the effect of single genes (47).

We observed a higher incidence of skin disease in female back-
cross mice (54%) than in male backcross mice (22%). This is in agreement with some reports on human psoriasis where it appears to be slightly more prevalent in women than in men (www.emedicine.com/oph/topic483.htm). A recent study found that the prevalence of psoriasis in the United Kingdom is greater in young female patients compared with young male patients and declines...
significantly in patients 70 years and older, regardless of sex (48). In
contrast, a recent survey of psoriasis in 694 patients from Nor-
way did not show any significant sex difference for both sexes
(49). Also, in a survey of psoriasis patients in Japan, evidence
points to a paternal overtransmission of psoriasis to males being
more frequently affected (65.8%) compared with females (34.2%)
(50). Thus, ethnic factors also appear to influence the sex preva-
ience of psoriasis. Similar to our observation, the difference in
susceptibility between sexes is a common feature of most models
for autoimmune diseases, like systemic lupus erythematosus, rheu-
matoid arthritis, and experimental autoimmune encephalomyelitis,
as well as of the human diseases (51), even though the sex effect
in some animal models is reversed compared with the human dis-
ease. The sexual dimorphism may be due to sex hormones, which
can influence the immune system (51–54).

Due to the current view that psoriasis is a T cell-mediated immu-
no logical disease (3), genes affecting immunological functions,
especially that of T cells, are most promising candidates. The cur-
rent mouse map (Mouse Genome Database) contains a number of
such candidate genes for the regions identified in the herein per-
formed linkage analysis (42). These include the IFN-γR, TNF-α-
induced protein, IL-22 binding protein, leukocyte Ig-like receptor
5, and gap junction protein-α1 on chromosome 10, as well as
CD8, CD207 (langerin), receptors for IL-5, -12, and -23, and
CXCL12 on chromosome 6. However, the regions identified in this
genome-wide linkage analysis are large and contain a considerable
number of genes. Therefore, the size of the support interval should
be reduced before performing candidate gene analyses.

The murine localizations of candidate regions can be used to
predict the positions of human candidate susceptibility loci. Prox-
imal mouse chromosome 10 exhibits extensive homology with hu-
man chromosome 6q16–25, whereas the central part of mouse
chromosome 6 shows homology with regions on different human
chromosomes, namely 2p13–11, 3p26–25, 3q21, and 4q22–27
(Mouse Genome Database). One of these regions (3q21) has al-
ready been described to be linked with psoriasis vulgaris
(PSORS1) (19). However, the underlying gene in this region has
not yet been identified. SLC12A8 coding for a member of the sol-
te carrier family 12 proteins has been suggested as candidate gene
(55). Two other candidate genes from this region, the zinc finger
protein 148 and cystatin A, could not be shown to be associated
with psoriasis in a large family set showing linkage to the PSORS5
locus (56). The corresponding human regions to the chromosome
1 and 4 loci identified in the present study are 1q23-44 (PSORS4)
and 1q36-22 (PSORS7), respectively, which have also shown link-
age with psoriasis vulgaris (18, 21). Therefore, it may be relevant
for human psoriasis to unravel the underlying genes involved in
the skin disease of the CD18hypo mouse model. However, strongest
linkage was observed for a region on the proximal part of chro-
mosome 10. The corresponding region in human located on
6q16-25 has not yet been identified in linkage analyses as being of
importance in psoriasis patients. The same is true for regions cor-
responding to the proximal end of chromosome 18, which are dis-
tributed on different human chromosomes on 5q22-33, 10p12-11,
and 18q11-12.

The CD18 gene is located in a region on human chromosome
21q, for which no linkage has so far been observed in studies with
psoriasis families. However, PSORS2 on 17q with ICAM-2 (15)
and PSORS6 on 19p with ICAM-1 (20) contain two genes coding
for the most important ligands of the β2 integrins. It might be that
in human psoriasis not only β2 integrins themselves but also com-
ponents essential for their signaling and/or effects could be altered.

The gene locus showing strongest linkage to psoriasis vulgaris
so far is PSORS1 on 6p21 (13, 14) containing, among others, the
MHC gene HLA-C. In the present backcross, the MHC/H2 region
was not demonstrated to be associated with skin disease develop-
ment. This is in accordance with observations in an earlier back-
cross between CD18hypo PL/J and C57BL/6J strains, which re-
vealed no correlation between the H2 region and the psoriasisform
skin disease (33). Even though we cannot fully exclude the pos-
sibility that the susceptible strain had lost the variation in the H2
locus during inbreeding, we now have preliminary data indicating
that congenic mice carrying PL/J alleles on chromosome 10 de-
veloped the psoriasisform skin phenotype (our unpublished data).
These data indicate that the H2 locus is not necessarily required for
the manifestation of the phenotype in this mouse model. However,
our finding that the H2 locus does not represent a major manifes-
tation in the mouse model does not argue against the involvement
of MHC in human psoriasis development. It is worth noting that
some of the chromosomal regions identified in the present study
have previously been shown to be susceptibility loci in mouse
models of other complex inflammatory diseases. The region on the
distal end of chromosome 1 was mapped in several diseases (47).
This region is supposed to contain genes important in a number of
processes leading to the development of autoimmune diseases
(57). Furthermore, the loci on chromosomes 6, 10, and 18 have
also been identified in studies of experimental autoimmune en-
cephalomyelitis (39). We have started to produce speed congenic
strains (58) for chromosome 10 and 6 candidate regions which will
allow exclusion of certain candidate genes listed above and reduce
the support interval to one that is amenable to physical mapping.
Indeed, this approach has earlier been successful in identifying
disease-causing genes (59). Because these genes identified in the
mouse model might also play a role in the human disease, genetic
analysis of CD18hypo mice may significantly contribute to the elu-
cidation of the pathogenesis of human psoriasis.

Acknowledgments
We are grateful to Samir Tawadros for his support in the mice facility with
animal care, Anja Böttger for technical help, and Dr. Werner Müller, Prof.
André Reis, and Prof. Thomas F. Wienczer for expertise in setting up the
backcross analyses.

Disclosures
The authors have no financial conflict of interest.

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