To determine the mechanism by which platelet counts increase after corticosteroid therapy for human immune thrombocytopenic purpura (ITP), we studied the platelet kinetics using prednisolone (PDN)-treated ITP-prone mice, (NZW × BXSB) F1 (W/B F1). An increase in platelet counts was observed in W/B F1 mice (n = 10, mean ± SD, 1,202 ± 202 ± 10^5/µL) 4 weeks after treatment with PDN (2 mg/kg/d); no increase occurred in nontreated W/B F1 mice (n = 5, 851 ± 126, P < .005). Prolonged platelet life-spans (PLSs) were observed in treated W/B F1 mice (1.29 ± 0.40 days), but not in nontreated controls (0.60 ± 0.24 days, P < .01). No increase in platelet production (platelet turnover) was found in PDN-treated W/B F1 mice, but significant decreases in platelet-associated antibodies (PAAs) and platelet-bindable serum antibodies (PBAs) were noted. Studies on organ localization of radiolabeled platelets showed that hepatic uptake significantly decreased in the treated W/B F1 mice, but not in nontreated W/B F1 mice. To elucidate the effect of PDN on the reticulo-endothelial phagocytic activity in W/B F1 mice, we studied in vivo clearance of IgG-sensitized, 125I-labeled autologous erythrocytes. W/B F1 mice treated with PDN showed a marked impairment of their ability to clear these cells, although PDN had little effect on the number of splenic or hepatic macrophage Fcγ receptors. These results and our previous findings of splenectomy suggest that PDN improves platelet counts not only by suppressing systemic reticulo-endothelial phagocytic function but also by reducing antibody production.

CHRONIC IMMUNE thrombocytopenic purpura (ITP) is an autoimmune disorder in which the destruction of autologous platelets is mediated by autoantibodies directed against platelet-surface antigens, resulting in their premature removal by the reticulo-endothelial system (RES), particularly the spleen and the liver. Despite the lack of a clear understanding of its etiology or pathophysiology, effective therapies for ITP have been developed. Corticosteroids are widely used as the initial therapy for ITP, including reduction of autoantibody production and suppression of reticuloendothelial phagocytic function. More recent kinetic studies suggest that corticosteroids improve platelet counts by increasing bone marrow platelet production. However, there is a lack of evidence to back up these hypotheses, and no useful animal model for ITP has been found. The exact mechanism, therefore, remains unknown.

We have recently found that male (NZW × BXSB) F1 mice (W/B F1), which spontaneously develop thrombocytopenia, show reduced platelet life-spans (PLSs) and increased platelet-associated antibodies (PAAs) as well as platelet-bindable serum antibodies (PBAs) with age. Our findings based on platelet transfer experiments using W/B F1 mice strongly suggest that PAAs on the platelet surface play a crucial role in the destruction of platelets by systemic RES.

In the present study, we show that the repeated injection of W/B F1 mice with prednisolone (PDN) leads to a remarkable increase in platelet counts. We further attempt to clarify which factors are responsible for the increase in platelet counts by studying in vivo platelet kinetics using this animal model. We show here that prolonged PLSs, decreased PAAs and PBAs, and impaired clearance of sensitized red blood cells (RBCs) are induced by PDN administration. This suggests that the increase in platelet counts induced by PDN is mediated by both the suppression of RES functions and the reduction of antibody production.

MATERIALS AND METHODS

Mice. BALB/c, BXSB, and NZW mice were originally purchased from Jackson Laboratories (Bar Harbor, ME). W/B F1 mice (hybrids of NZW females and BXSB males) were raised under specific pathogen-free conditions in the animal facility of Kiwa Experimental Animal Laboratories (Wakayama, Japan).

Platelet counts. Blood (20 µL) was diluted in a buffer containing ammonium oxalate (Unopette Kits, Becton Dickinson, Sunnyvale, CA). Platelets were counted using a hematocytometer under a phase-contrast microscope.

Prednisolone treatment. Each mouse was intraperitoneally (IP) injected daily for 4 weeks with PDN (Predonine; Shionogi Pharmaceutical Co, Osaka, Japan) (2 mg/kg in 0.1 mL of isotonic saline). Control mice received the same volume of saline. No mice died during treatment, and all mice survived for more than 3 weeks after the end of treatment.

Platelet labeling and kinetics studies. 111In-tropolone was used for the labeling of platelets. Details of the methods are described elsewhere. Recipient mice were injected intravenously with the radiolabeled platelets (approximately 185 KBq in 0.2 mL). Blood (15 µL) was then taken 1 minute, 30 minutes, 1 hour, 2 hours, 4 hours, 24 hours, and 48 hours after injection, and the radioactivity counted using a well-typed scintillation counter. The mean PLS was estimated by calculating the rate of platelet disappearance...
from circulation using multiple-hit model analyses, as recom-
manded by the International Committee for Standardization in
Hematology. Extrapolation of the platelet survival curve to time
turnover was used in the determination of platelet recovery, which was
calculated as

\[
\text{Turnover} = \frac{\text{Platelet Count} \times 10^{12}/\mu L \times 90}{\text{Platelet Lifespan (days) \times Platelet Recovery (\%)}}
\]

For stable platelet counts, it is assumed that platelet turnover equals platelet production. Mice were killed 72 hours after injection to determine the organ localization of the radiolabeled platelets. The liver, spleen, lungs, and bone marrow (femurs) were removed to determine the level of radioactivity in the organs.

**RESULTS**

**Effect of PDN treatment on the platelet counts in W/B F, mice.** Figure 1 illustrates the changes in platelet counts after PDN treatment. Platelet counts of 1-month-old W/B F, mice were 1,105 ± 134 × 10^3/μL (n = 5, shaded area). Three-month-old W/B F, mice (male) already showed thrombocytopenia (n = 15, 702 ± 105 × 10^3/μL). PDN led to an increase in platelet counts in W/B F, mice (n = 10, 854 ± 128 × 10^3/μL) 2 weeks after PDN treatment. Three or 4 weeks after PDN treatment, the increase in W/B F, mice (3 weeks, 1,022 ± 125 × 10^3/μL; 4 weeks, 1,202 ± 202 × 10^3/μL) became statistically significant, in comparison with controls (n = 5, 642 ± 62 × 10^3/μL; P < .001).

**Macrophone Fcγ receptor (FcγR) assay.** Macrophone FcγR expression was assessed by the binding of 2.4G2 (rat monoclonal antibody against antimouse FcγII receptor) according to the methods of Petroni et al. Briefly, spleen mononuclear cell suspensions isolated from the density gradient were washed three times in 5 mmol/L EDTA-PBS with 0.1% sodium azide. Splenic macrophage-rich fractions were then obtained by the plastic dish method. For the isolation of hepatic macrophages, liver was minced and washed twice with Hank's balanced salt solution (HBSS), then incubated at 37°C for 60 minutes with 5 mL of HBSS containing 2.5 mg of collagenase (type II; Sigma Chemical Co, St Louis, MO) and 1.0 mg of trypsin inhibitor (type 1-Sigma). The resulting cell suspension was filtered by passing it through sterile cotton gauze and centrifuged three times at 60g for 1 minute to remove hepatocytes. The supernatant was washed three times with HBSS and resuspended with EDTA-PBS. This hepatic or splenic macrophage-rich fraction (more than 50% were morphologically identified as macrophage, 1 × 10^9/100 μL) was incubated with saturating concentrations of purified 2.4G2 or rat IgG at 4°C for 30 minutes. After washing three times in EDTA-PBS, the cells were then incubated with 50 μL of FITC-conjugated rabbit F(ab')2 directed against rat Ig (Serotec Co, Oxford, UK; 1:100 dilution) for 30 minutes. After final washing, macrophages were sectioned with the scatter-gating method, and a total of 1 × 10^5 cells within the gate were analyzed using a FACScan. Data were expressed as FR (as described above).

**Statistical analyses.** The means of platelet counts, PLSs, and PAAs were compared using a paired or unpaired Student's t-test at the .05 significance level.

![Graph](Fig 1. The effect of PDN on platelet counts in W/B Fj mice. Mice were treated with PDN (2 mg/kg/d) for 4 weeks (n = 10, []). Control W/B Fj mice were treated with the same volume of isotonic saline (n = 5, □). Bars represent mean ± SD. Shading shows the normal range of platelet counts (1-month-old W/B Fj). (*) P < .001.)
The control W/B F, mice, which were treated with isotonic saline alone, showed a slight decrease in platelet counts with age (Fig 1), which was similar to the platelet counts of nontreated W/B F, mice (data not shown); this decrease with age was considered to be a natural course of the disease.

Platelet kinetic studies. Table 1 shows the PLSs of each mouse before and after treatment. The PLSs of male BALB/c (3 months) and female W/B F, (3 months) mice were 2.11 ± 0.28 and 1.44 ± 0.21 days, respectively, whereas those of male W/B F, (3 months) mice were significantly shortened (0.60 ± 0.24 days). Four weeks after PDN treatment, a significant prolongation of PLSs was observed (1.29 ± 0.40 days), in contrast to controls (0.47 ± 0.32 days; P < .01); values were also significantly prolonged in contrast to those before PDN treatment (0.60 ± 0.24 days; P < .01). The effect of PDN treatment on platelet recovery and platelet turnover is also shown in Table 1. The male W/B F, mice showed a significantly increased platelet turnover, in contrast to the male BALB/c and female W/B F, mice (P < .01), which showed no such increase. Four weeks after PDN treatment, a decreased turnover was observed in W/B F, mice (1,579 ± 252 × 10⁹ platelets/µL/d), in contrast to nontreated W/B F, mice (2,297 ± 364; P < .05). Table 2 summarizes the uptake of ⁵¹In-labeled platelets by major organs 3 days after injection. The spleen and liver of male W/B F, mice were the main accumulation sites of labeled platelets; the mice showed mild hepato-splenomegaly. A slight but significant decrease in hepatic uptake was noted in PDN-treated W/B F, mice, in contrast to nontreated controls (P < .05, Table 2).

PAAs and PBAs. Figure 2 shows the representative data regarding flow cytometric changes in PAA and PBA values of a single mouse. Four weeks after PDN treatment, a significant decrease both in PAA (FR, mean ± SD) (before, 4.9 ± 2.8; after, 2.4 ± 0.8; n = 5, P < .05) and PBA values (before, 4.4 ± 0.9; after, 2.2 ± 0.8; n = 5, P < .01) was observed. The peak channel of fluorescence intensity of PAA's and PBAs on FACS analyses shifted to the left after PDN treatment (Fig 2C and D), whereas that of the control W/B F, mice shifted to the right, suggesting that both PAA and PBA values increased (Fig 2A and B) 4 weeks after PDN treatment. No significant decrease in PAA or PBA values was found 2 weeks after initiation of PDN treatment (PAA, 4.4 ± 2.3; PBA, 3.9 ± 1.1).

Clearance of IgG-coated RBCs. ⁵²Cr-labeled RBCs coated with IgG antibody were injected into 3-month-old W/B F, mice, and the fate of the cells then determined (Fig 3). Nontreated W/B F, mice (n = 4) showed a rapid clearance of these cells, whereas W/B F, mice treated with PDN for 4 weeks (n = 4) showed a much lower clearance rate. At 2 hours, 35% ± 12% (mean ± SD) of the IgG-coated RBCs remained in the circulation in the treated group, compared with 11% ± 6% in the controls (P < .05). ⁵²Cr-labeled, nonsensitized RBCs were not removed from the circulation (Fig 3).

Effect of PDN treatment on macrophage FcγR expression. To evaluate the effect of PDN on the FcγR number of splenic or hepatic macrophages, we analyzed the macrophage FcγR expression using the rat monoclonal antibody (2.4G2) that specifically binds to FcγR II on mouse macrophages. Table 3 shows the FcγR expression of W/B F, mice after 4 weeks of PDN treatment. Although the expression of FcγR on hepatic or splenic macrophages from PDN-treatment mice slightly decreased, no statistically significant change was found by FACS analyses, suggesting that PDN has little effect on the number of FcγRs.

**DISCUSSION**

A number of investigators have studied the effects of corticosteroids on experimentally induced hemolytic anemia or thrombocytopenia in animals. In most experiments, heterologous antisera were injected directly in animals, and kinetics studies were then performed. These studies differed from ours in that they were not able to systematically examine the in vivo effects of PDN on autoantibody production, etc, because these animals do not spontaneously produce antplatelet antibodies. In contrast, W/B F, mice spontaneously produce antplatelet antibodies resulting in thrombocytopenia. We therefore consider the W/B F, mouse to be a useful animal model for the investigation of the mode of action of corticosteroids in ITP.

W/B F, mice are known to develop systemic lupus erythematosus-like diseases and show high levels of circulating immune complexes (CICs). It is therefore conceiv-

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**Table 1. Effect of PDN Treatment on Platelet Kinetics in W/B F, Mice**

<table>
<thead>
<tr>
<th>Mouse</th>
<th>Age (mo)</th>
<th>Sex</th>
<th>No.</th>
<th>PDN Treatment</th>
<th>Platelet Recovery (%)</th>
<th>Platelet Lifespan (d)</th>
<th>Platelet Turnover (×10⁹ platelets/µL·d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BALB/c</td>
<td>3</td>
<td>M</td>
<td>6</td>
<td>−</td>
<td>77.3 ± 7.2</td>
<td>ND</td>
<td>2.11 ± 0.28</td>
</tr>
<tr>
<td>W/B F</td>
<td>3</td>
<td>F</td>
<td>5</td>
<td>−</td>
<td>72.4 ± 4.9</td>
<td>ND</td>
<td>1.44 ± 0.21</td>
</tr>
<tr>
<td>W/B F</td>
<td>3</td>
<td>M</td>
<td>5</td>
<td>−</td>
<td>58.2 ± 8.4</td>
<td>50.2 ± 5.9</td>
<td>0.62 ± 0.35</td>
</tr>
<tr>
<td>W/B F</td>
<td>3</td>
<td>M</td>
<td>10</td>
<td>+</td>
<td>56.6 ± 7.5</td>
<td>59.2 ± 9.4</td>
<td>0.60 ± 0.24</td>
</tr>
</tbody>
</table>

Platelet recovery, platelet lifespan, and platelet turnover were calculated as described in Materials and Methods. Mice were examined 4 weeks after PDN treatment. Values represent mean ± SD.

Abbreviation: ND, not determined.

* Mice were treated with equal volumes of isotonic saline for 4 weeks.

**P** < .01 versus data in female W/B F, mice.

*P* < .05 versus data in nontreated W/B F, mice. and *P* < .01 versus data in W/B F, mice before PDN treatment.

*P* < .05 versus data in nontreated W/B F, mice.

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Table 2. Organ Distribution of \[^{115}\text{In}-\text{Labeled Autologous Platelets in W/B F, Mice}

<table>
<thead>
<tr>
<th>Mouse</th>
<th>Age (mo)</th>
<th>Sex</th>
<th>No.</th>
<th>PDN Treatment</th>
<th>Weight (mg)</th>
<th>% Distribution</th>
<th>Liver</th>
<th>Spleen</th>
<th>Liver</th>
<th>Spleen</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/B F, 3</td>
<td>3</td>
<td>F</td>
<td>5</td>
<td>-</td>
<td>1,190 ± 120</td>
<td>32 ± 7</td>
<td>21 ± 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/B F, 3</td>
<td>3</td>
<td>M</td>
<td>5</td>
<td>+</td>
<td>1,800 ± 310</td>
<td>29 ± 5</td>
<td>25 ± 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/B F, 3</td>
<td>3</td>
<td>M</td>
<td>5</td>
<td>+</td>
<td>1,720 ± 260</td>
<td>330 ± 72</td>
<td>21 ± 48</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Mice were killed 72 hours after injection of labeled platelets, and percentage of radioactivity totally injected then determined. Values represent mean ± SD.
†Mice were treated with isotonic saline for 4 weeks.
‡P < .05 versus data in nontreated male W/B F, mice.

able that CICs are involved in thrombocytopenia in these mice. However, we think that the increased PAA levels are not due to the absorption of CICs because (1) murine platelets have no Fc receptor;
(2) other typical SLE-prone mice such as BXSB, MRL/lpr, and NZB/NZW F, which show high CIC levels, have normal platelet counts; (3) the sera from these mice do not bind to platelets of normal mice; and (4) purified F(ab') fragments of W/B F, IgG can also bind to normal platelets (unpublished data).

In this study, we have shown that PDN leads to increased platelet counts and prolonged PLTs in W/B F, mice. Clearance studies using IgG-coated RBCs also showed a significant suppression of the ability to clear these cells. These observations suggest that one of the mechanisms of action of PDN is the suppression of the reticulo-endothelial phagocytic function. Consequently, PDN may modulate PLTs and increase platelet counts. Furthermore, marked decreases in PAA and PBA values were noted after PDN treatment in W/B F, mice, suggesting that another mechanism of PDN is the reduction of autoantibody production. It remains uncertain which mechanism is the most important with regard to the increased platelet counts in these mice, although we think that for at least 2 weeks after the treatment, PDN may act by suppressing reticulo-endothelial phagocytic activity, rather than by reducing antibody production, as platelet counts increased extremely rapidly (within 2 weeks) without any significant changes in the PAA or PBA values.

Another possible effect of PDN on PAA and PBA values is impairment of the interaction between antibodies and antigens, resulting in decreased binding of antibodies to platelets. Although this is conceivable, it seems unlikely, because PDN cannot interfere with the binding of serum antiplatelet antibodies to platelets for long periods without any significant reduction in antibody production.

We have recently examined the effect of splenectomy on platelet kinetics in W/B F, mice, and found that platelet counts increased and PLTs were prolonged, but normal levels were not reached even after splenectomy; splenectomy had little effect on either PAA or PBA values. From these findings, we consider that the limited effect of splenectomy may be explained by the presence of the systemic RES other than the spleen. In the present study, PDN showed a greater therapeutic effect on platelet counts than splenectomy. It is therefore likely that PDN improves platelet counts not only by suppressing antibody production but also by blocking the systemic RES (including the spleen).

Recently, Gernsheimer et al showed that platelet production was impaired in some ITP patients. If this is the case, PDN may improve the platelet count by increasing platelet production. However, in nontreated W/B F, mice, increased platelet turnover (platelet production) was observed, and a relatively reduced platelet turnover was noted in PDN-treated W/B F, mice. These findings indicate that, in W/B F, mice, both platelet production and destruction...
were examined platelet destruction rather than by increasing platelet production. This suggests that corticosteroids influence the RES by either suppressing systemic reticuloendothelial phagocytic function but also by reducing autoantibody production, and that they have little effect on platelet production.

The exact mechanism of PDN-induced suppression of the RES has not been fully defined. One interesting finding of our study on organ distribution is that PDN induces a relative decrease in hepatic uptake compared with non-treated controls, without a significant change in splenic uptake. These findings suggest that PDN may act by either directly suppressing the phagocytic activity of Kupffer cells or by modulating the hepatic blood flow. In either case, the present findings are consistent with our previous findings that the limited effect of splenectomy may be due to the presence of the systemic RES other than the spleen (probably the liver).

are accelerated, and that PDN may act by suppressing platelet destruction rather than by increasing platelet production. We conclude that corticosteroids improve platelet counts in W/B F mice not only by suppressing systemic reticuloendothelial phagocytic function but also by reducing autoantibody production, and that they have little effect on platelet production.

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Mechanisms of corticosteroid action in immune thrombocytopenic purpura (ITP): experimental studies using ITP-prone mice, (NZW x BXSB) F1

H Mizutani, T Furubayashi, Y Imai, H Kashiwagi, S Honda, H Take, Y Kurata, T Yonezawa, S Tarui and S Ikehara