G-Rich DNA Suppresses Systemic Lupus

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Whereas the role of immune complexes in mediating renal cell and immune cell activation is well established, the contribution of sequence-specific immunomodulatory actions of the chromatin part remains unclear. Toll-like receptor-9 (TLR-9) mediates immunostimulatory effects of unmethylated microbial CpG-DNA. It was hypothesized that hypomethylated CpG-DNA in vertebrates may have similar effects and may contribute to disease progression in lupus nephritis. A synthetic G-rich DNA, known to block CpG-DNA effects, was used in this study. In macrophages, G-rich DNA suppressed CpG-DNA– but not LPS-induced production of CCL5 in a dose-dependent manner. Injections of G-rich DNA suppressed lymphoproliferation induced by CpG-DNA injections in mice. In MRL<sup>lpr/lpr</sup> mice with lupus nephritis, labeled G-rich DNA co-localized to glomerular immune complexes and was taken up into endosomes of TLR-9–positive infiltrating macrophages. Eleven-week-old MRL<sup>lpr/lpr</sup> mice that received injections of either saline or G-rich DNA for 13 wk revealed decreased lymphoproliferation and less autoimmune tissue injury in lungs and kidneys as compared with saline-treated controls. G-rich DNA reduced the levels of serum dsDNA-specific IgG2a as well as the renal immune complex deposits. This was consistent with the blocking effect of G-rich DNA on CpG-DNA–induced proliferation of B cells that were isolated from MRL<sup>lpr/lpr</sup> mice. As oligodeoxyribonucleotide 2114–treated MRL<sup>lpr/lpr</sup> mice were not exposed to exogenous CpG-DNA, these effects should relate to a blockade of CpG motifs in endogenous DNA. It is concluded that adjuvant activity of self-DNA contributes to the pathogenesis of lupus nephritis. Modulating the CpG-DNA–TLR-9 pathway may offer new opportunities for the understanding and treatment of lupus.


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Materials and Methods

Phosphodiester ODN

The following ODN were used for in vitro or in vivo studies. ODN 2114 5'-TCC TGG AGG GGA AGT-3', CpG-ODN 1668 5'-TGG ATG ATG TTC CTC ATG CT-3', and CpG-ODN 1720 5'-TCC ATG AGC TTC CTG ATG CT-3' (TIB Molbiol, Berlin, Germany).

Animal Studies

Eight-week-old female 129Sv mice were obtained from Taconic (Ry, Denmark). Ten-week-old female MRL lrpr/lpr mice were obtained from Harlan Winkelmann (Borchen, Germany) and were kept in filter-top cages under a 12-h light/dark cycle. Autoclaved water and standard Harlan Winkelmann (Borchen, Germany) and were kept in filter-top cages under a 12-h light/dark cycle. Autoclaved water and standard

Cell Culture Conditions

J774 mouse macrophages (American Type Culture Collection, Rockville, MD) were grown in RPMI 1640 that contained 1 mM HEPES, 10% heat-inactivated bovine serum, 100 units/ml penicillin, and 100 μg/ml streptomycin (Biochrom KG, Berlin, Germany). B cells were isolated from spleens of female MRL lrpr/lpr mice using B Cell Isolation Kit. Ten-week-old female MRL lrpr/lpr mice were obtained from Taconic (Ry, Denmark). Eight-week-old female 129Sv mice were obtained from Taconic (Ry, Denmark). Ten-week-old female MRL lrpr/lpr mice were obtained from Harlan Winkelmann (Borchen, Germany) and were kept in filter-top cages under a 12-h light/dark cycle. Autoclaved water and standard Harlan Winkelmann (Borchen, Germany) and were kept in filter-top cages under a 12-h light/dark cycle. Autoclaved water and standard

Cytokine and Nitric Oxide Analysis

Cytokine levels in mice sera or cell culture supernatants were determined using commercial ELISA kits: Mouse TNF-α (Biologend, San Diego, CA), CCL5 (R&D, Wiesbaden-Nordenstadt, Germany), and IFN-α (Peproscience, Bonn, Germany). The Griess Reagent System (Promega) was used for the determination of nitrite in cell supernatants as a marker of nitric oxide production.

Statistical Analyses

Data were expressed as mean ± SEM. Cell culture data were analyzed using ANOVA, and post hoc Bonferroni correction was used for multiple comparisons. Comparison of groups of mice was performed using unpaired two-tailed t test. P < 0.05 was considered to indicate statistical significance.

Results

ODN 2114 Blocks Stimulatory Activity of CpG-ODN In Vitro

ODN 2114 have been reported to block CpG-ODN–induced NF-κB activation in mouse B cells (16). We first aimed to confirm this blocking effect in murine macrophages. ODN 2114 blocked CpG-ODN–induced CCL5 (Figure 1A) and nitric oxide (Figure 1B) production in J774 monocytes in a dose-dependent manner. At equimolar concentrations of CpG-DNA and ODN 2114, the blocking effect of ODN 2114 on nitric production was 100%. By contrast, ODN 2114 did not affect CCL5 or TNF-α production induced by LPS (Figure 1, C and D). These data suggest that ODN 2114 can act as a specific antagonist for CpG-ODN–induced activation of mouse monocytes in vitro.

ODN 2114 Blocks Stimulatory Activity of CpG-ODN In Vivo

Next we assessed the potential of ODN 2114 to block the reported CpG-ODN–induced toxicity after repeated injection in mice (3). We treated 129Sv mice with daily intraperitoneal injections of saline or either 60 μg CpG-ODN, GpC-ODN, ODN 2114, or CpG-ODN plus ODN 2114 or saline for 12 d (n = 5 in each group). As previously reported, CpG-ODN induced splenomegaly and lymphadenopathy as compared with saline-injected mice (3). In spleens and lymph nodes, total cellularity was increased and follicles were replaced by disorganized collections of activated macrophages (Figure 2). All CpG-ODN–treated mice showed hemorrhagic ascites, as compared with saline and ODN 2114–treated controls, whereas ODN 2114 completely blocked CpG-ODN–induced ascites production. Livers of these mice revealed multifocal portal inflammatory cell infiltrates associated with large areas of necrotic and apoptotic hepatocytes (Figure 2). By contrast, all mice that received ODN 2114 injections together with CpG-ODN did not show major signs of CpG-ODN toxicity. ODN 2114 also significantly reduced CpG-ODN–induced alterations of the microarchitecture in spleens and lymph nodes (Figure 2). Mice that received injections with either ODN 2114 or CpG-ODN alone did not show any histopathologic abnormalities as compared with saline-injected mice (data not shown), the latter excluding unspe-
specific competition of CpG-DNA. These data implicate that ODN 2114 can block CpG-ODN–induced effects
in vivo in mice.

Distribution of Labeled ODN 2114 and CpG-ODN of Autoimmune MRL<sub>lpr/lpr</sub> Mice

In view of our previous findings that exogenous CpG-DNA is taken up by intrarenal macrophages (7), we questioned whether injected ODN 2114 localizes likewise in nephritic kidneys of MRL<sub>lpr/lpr</sub> mice. Thus, we studied the distribution of rhodamine-labeled ODN 2114 in nephritic kidneys of 16-wk-old MRL<sub>lpr/lpr</sub> mice. After intravenous injection, ODN 2114 were detected in a glomerular mesangial and capillary staining pattern (Figure 3A). Co-staining with an anti-mouse IgG antibody showed co-localization of labeled ODN 2114 with glomerular IgG deposits (Figure 3B). In some areas, ODN 2114–positive granules were negative for IgG (Figure 3C). Co-staining with an EH-HR3 antibody identified these granules to be endosomes of glomerular macrophages but IgG–ODN 2114 double-positive endosomes were also observed (Figure 3D). Co-staining with a TLR-9 antibody confirmed co-localization of ODN 2114 with glomerular IgG deposits (Figure 3B). In some areas, ODN 2114–positive granules were negative for IgG (Figure 3C). Co-staining with an EH-HR3 antibody identified these granules to be endosomes of glomerular macrophages but IgG–ODN 2114 double-positive endosomes were also observed (Figure 3D). Co-staining with a TLR-9 antibody confirmed co-localization of ODN 2114 with TLR-9 (Figure 3E). Nephritic MRL<sub>lpr/lpr</sub> mice that received an injection of rhodamine only or healthy MRL wild-type mice that received an injection of labeled ODN 2114 did not show any glomerular deposits (data not shown). These findings show that injected ODN 2114 localize to glomerular...
mesangium and capillaries and are taken up into TLR-9–positive intracellular endosomes of glomerular macrophages.

ODN 2114 Protect MRL<sup>lpr/lpr</sup> Mice from Autoimmune Tissue Injury

On the basis of these data, we hypothesized that ODN 2114 might modulate macrophage function in experimental lupus. We treated MRL<sup>lpr/lpr</sup> mice from week 11 to week 24 of age with intraperitoneal injections of ODN 2114 on alternate-day intervals and compared markers of disease activity with saline-treated MRL<sup>lpr/lpr</sup> mice at the end of the study. We observed that ODN 2114 reduced spleen weight in MRL<sup>lpr/lpr</sup> mice as compared with saline-treated controls (Table 1). Morphometric analysis revealed less tissue injury in kidneys and lungs of ODN 2114–treated mice (Table 1). Lungs of ODN 2114–treated mice showed less peribronchiolar and perivascular inflammatory cell infiltrates compared with saline-treated controls (Figure 4). In kidneys of MRL<sup>lpr/lpr</sup> mice, ODN 2114 significantly reduced the number of interstitial ER-HR3 macrophages, CD3 lymphocytes, and Ki-67–positive proliferating cells in glomeruli and the tubular compartment (Table 1, Figure 5A). Proteinuria as a marker of glomerular injury was also reduced, although the altogether low glomerular ER-HR3 macrophage and CD3 T cell counts were similar in both groups (Table 1).

ODN 2114 Block B Cell–Dependent Autoimmunity in MRL<sup>lpr/lpr</sup> Mice

Autoantibody production and immune complex deposition cause tissue injury in lupus. Thus, we assessed the effect of ODN 2114 on DNA autoantibody production and renal immune complex deposits in MRL<sup>lpr/lpr</sup> mice. At 24 wk, ODN 2114–treated MRL<sup>lpr/lpr</sup> mice revealed reduced serum levels of dsDNA-specific IgG<sub>2a</sub> antibodies as compared with saline-treated MRL<sup>lpr/lpr</sup> mice (Figure 6A). This was consistent with the observation that ODN 2114 markedly reduced glomerular IgG<sub>2a</sub> deposits in MRL<sup>lpr/lpr</sup> mice (Figure 6B, Table 1). Glomerular IgG<sub>1</sub> deposits were not reduced, indicating that the effect of ODN 2114 on serum IgG<sub>1</sub> levels relates to their specificity for dsDNA. These findings are suggestive of an inhibitory effect of ODN 2114 on dsDNA–induced B cell proliferation in MRL<sup>lpr/lpr</sup> mice. Therefore, we isolated B cells from MRL<sup>lpr/lpr</sup> mice and studied the effects of ODN 2114 on either CpG-DNA- or LPS-induced B cell proliferation in vitro. ODN 2114 blocked B cell proliferation in a dose-dependent manner when cells were exposed to CpG-DNA (Figure 7A). By contrast, ODN 2114 had no effect on LPS-induced B cell proliferation (Figure 7B). These data suggest that ODN 2114 specifically block CpG-ODN–induced B cell proliferation as well as subsequent DNA autoantibody production and renal immune complex deposits in MRL<sup>lpr/lpr</sup> mice.

Discussion

When MRL<sup>lpr/lpr</sup> mice are exposed to bacterial or synthetic CpG-DNA, ligation of TLR-9 on immune cells leads to enhanced dsDNA autoantibody production and aggravation of lupus nephritis (7). Similarly, insufficient clearance of nuclear particles in lupus may also provide a permanent source of hypomethylated CpG motifs from self DNA (22). This mechanism may contribute to a continuous activation of B cells and dendritic cells and perpetuate systemic lupus in humans (10,23,24). In this study, we addressed this hypothetical pathway by blocking potential CpG-DNA–induced immunity both in vitro and in vivo with a specific antagonist, G-rich DNA. We
further argued that if endogenous CpG-DNA were to contribute to the progression of lupus nephritis, then injections of G-rich DNA should prevent disease progression in MRL<sup>lpr/lpr</sup> mice with experimental lupus.

Synthetic G-Rich ODN Neutralizes CpG-DNA

CpG-DNA is a strong activator of plasmacytoid dendritic cells, macrophages, and B cells in mice (10,25). CpG-DNA stimulates their antigen presentation and proinflammatory cytokine production that drive subsequent Th1-type responses (25). Lenert et al. (16) first used the ODN 2114 to block CpG-ODN–induced effects on murine B cells. Here we confirm that this antagonistic effect is specific, as the G-rich ODN 2114, which totally prevented CpG-DNA–induced B cell proliferation or CCL5 and TNF-α production by macrophages, did not modulate LPS-related effects. This antagonism occurs proximal to NF-κB activation (16), but the specific site of interaction is yet unknown. Competition for intracellular uptake of CpG-DNA was shown to be independent of G-rich motifs and far too weak to explain the 100% antagonism at equimolar concentrations of G-rich- and CpG-DNA (14,15). Alternatively, G-rich ODN may either compete with CpG-DNA for the CG binding site at TLR-9 (26) or modify the nanoparticle structure of nucleosomes by direct interaction with endogenous CpG-DNA (26,27). The latter would require co-localization of injected G-rich DNA chromatin particles. This may occur in vivo because we observed co-localization of injected ODN 2114 with glomerular IgG deposits that are complexed with chromatin-particles in nephritic MRL<sup>lpr/lpr</sup> mice. However, as our study was not designed to address this question, the interaction of CpG-DNA with TLR-9 on a molecular level remains to be determined. Nevertheless, G-rich ODN represents a specific antagonist for CpG-DNA–induced B cell and monocyte activation in mice. This was also confirmed in vivo by our experiments in Sv129 mice. G-rich ODN 2114 blocked CpG-ODN–induced lymphoproliferation, an effect shown to be mediated through TLR-9 on marginal zone B cells and monocytes (3) Together, G-rich ODN 2114 specifically block the effects of CpG-DNA in vitro and in vivo, which renders ODN 2114 a valuable tool to address the question, whether endogenous CpG-DNA can modulate lupus erythematosus.

G-Rich DNA Modulates Systemic Autoimmunity in MRL<sup>lpr/lpr</sup> Mice

Systemic lupus is associated with polyclonal B cell proliferation and DNA autoantibody production in humans. In MRL<sup>lpr/lpr</sup> mice, lymphoproliferation and dsDNA autoantibody production progress with age. Injections with G-rich ODN 2114 reduced spleen weight as a marker of lymphoproliferation as well as serum dsDNA autoantibody concentrations as compared with saline-injected MRL<sup>lpr/lpr</sup> mice. As the MRL<sup>lpr/lpr</sup> mice were not exposed to exogenous CpG-DNA, the observation may be attributed to a blockade of immunostimulatory effects of endogenous CpG-DNA on B cells. This is consistent with a study published by Leadbetter et al. (8) showing that self chromatin-containing immune complexes stimulate B cells iso-

<table>
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<th>Table 1. Serum, urinary, and histologic findings in kidneys of 24-wk-old MRL&lt;sup&gt;lpr/lpr&lt;/sup&gt; mice that received injections from 11 to 24 weeks of age&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Saline ($n = 9$)</th>
<th>ODN 2114 ($n = 10$)</th>
<th>$p$</th>
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<tr>
<td>Spleen weight</td>
<td>0.80 ± 0.13</td>
<td>0.56 ± 0.14</td>
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<td>Lung histologic score</td>
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<td>Proteinuria (μg/mg creatinine)</td>
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<td>Activity index</td>
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<td>Chronicity index</td>
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<td>Glomerular EHR&lt;sup&gt;+&lt;/sup&gt; (cells/glom)</td>
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<td>CD3&lt;sup&gt;+&lt;/sup&gt; (cells/glom)</td>
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<td>Ki-67&lt;sup&gt;+&lt;/sup&gt; (cells/glom)</td>
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<td>7.0 ± 4.8</td>
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<td>Interstitial EHR&lt;sup&gt;+&lt;/sup&gt; (cells/hpf)</td>
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<td>39.1 ± 12.9</td>
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<td>CD3&lt;sup&gt;+&lt;/sup&gt; (cells/hpf)</td>
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<td>7.4 ± 3.2</td>
<td>0.05</td>
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<td>Ki-67&lt;sup&gt;+&lt;/sup&gt; (cells/hpf)</td>
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<td>2.8 ± 1.1</td>
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<td>Tubular Ki-67&lt;sup&gt;+&lt;/sup&gt; (cells/hpf)</td>
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<td>1.1 ± 0.2</td>
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<td>Humoral response (glomerular deposit score)</td>
<td>2.5 ± 0.3</td>
<td>1.7 ± 0.5</td>
<td>0.003</td>
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<sup>a</sup>Values are means ± SEM from 8 to 10 mice per group.
lated from MRL<sup>lpr/lpr</sup> mice via TLR-9. It is noteworthy that suppressive ODN as well as DNAse treatment of the immune complexes abrogated this effect, supporting the role for the endogenous CpG-DNA in this context (8). In our study, the blocking effect of G-rich DNA on B cell proliferation was specific for CpG-DNA, because ODN 2114 did not modulate LPS-induced B cell proliferation.

Serum IFN-β levels depict the activation of IFN-producing plasmacytoid dendritic cells, which represents another marker for disease activity in lupus (28). Nuclear particles released from dying cells and complexed with lupus patient IgG are potent inducers of IFN-α production in plasmacytoid dendritic cells, an effect that is sensitive to DNAse digestion (29). In a recent study, immune complexes were isolated from sera of patients with various rheumatic diseases (16). It was found that only DNA-containing immune complexes that were isolated from lupus patients stimulated plasmacytoid dendritic cells to produce cytokines and chemokines via a cooperative interaction between TLR-9 and FcγRIIa (CD32). CD32 shuttles DNA-containing immune complexes into a subcellular compartment that contains TLR-9 (9). Only CD32-positive plasmacytoid dendritic cells internalized DNA-immune complexes and produced large amounts of IFN-α. Our finding that MRL<sup>lpr/lpr</sup> mice that received injections of G-rich DNA showed lower serum IFN-α levels as compared with saline-injected MRL<sup>lpr/lpr</sup> mice is in favor of a blocking effect of G-rich DNA on IFN-producing plasmacytoid dendritic cells. Thus, G-rich DNA can block B cell proliferation, dsDNA autoantibody production, and IFN-α release in MRL<sup>lpr/lpr</sup> mice, which all have established etiopathogenic roles in the systemic autoimmunity of lupus erythematosus.

G-Rich DNA Prevents Tissue Injury in MRL<sup>lpr/lpr</sup> Mice

MRL<sup>lpr/lpr</sup> mice that received injections of G-rich DNA had markedly reduced renal and pulmonary autoimmune tissue injury as compared with saline-injected mice. In part this may relate to the reduced anti-dsDNA antibody production and immune complex deposition, as demonstrated for the kidney. However, injected G-rich ODN 2114 could also interact locally with immune complexes and TLR-9-positive immune cells. We addressed this issue by injecting fluorescently labeled ODN 2114 into nephritic MRL<sup>lpr/lpr</sup> mice. In fact, ODN 2114 localized to glomerular immune complex deposits and to intracellular

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**Figure 4.** Autoimmune lung injury in MRL<sup>lpr/lpr</sup> mice. Lung sections that were taken from 24-wk-old MRL<sup>lpr/lpr</sup> mice were stained with PAS. Note that ODN 2114–treated MRL<sup>lpr/lpr</sup> mice show less peribronchiolar and perivascular inflammatory cell infiltrates as compared with saline-injected MRL<sup>lpr/lpr</sup> mice. Magnification, ×200.

**Figure 5.** Lupus nephritis in MRL<sup>lpr/lpr</sup> mice. (A) Renal sections were stained with PAS, ER-HR3, and CD3 as indicated. Images are representative of 10 mice in each group. Note that ODN 2114–treated MRL<sup>lpr/lpr</sup> mice show less periglomerular and interstitial inflammatory cell infiltrates as compared with saline-treated MRL<sup>lpr/lpr</sup> mice. (B) Serum IFN-β levels in 24-wk-old female saline- or ODN 2114–treated MRL<sup>lpr/lpr</sup> mice were determined by ELISA (n = 8 in each group). *P < 0.05 as compared with saline. Magnification, ×400 in A.
compartments of infiltrating glomerular macrophages. This cellular distribution was comparable to that of TLR-9 immunostaining in kidneys of MRL1pr/lpr mice. Thus, ODN 2114 could interfere with CpG-DNA–rich chromatin-immune complexes in the endosomes of intrarenal macrophages in vivo. This could reduce a proinflammatory effect of the immune complexes on macrophages and possibly dendritic cells in kidneys of MRL1pr/lpr mice. We showed previously that exogenous bacterial DNA or CpG-DNA markedly stimulate renal macrophages in lupus nephritis of MRL1pr/lpr mice and antigen-induced immune complex glomerulonephritis (4,7). CpG-DNA stimulates macrophages to produce multiple proinflammatory mediators that contribute to the progression of renal disease. Similarly, exogenous CpG-DNA can cause macrophage-dependent arthritis or lung injury, which both can be blocked with G-rich DNA (17,30). However, in this study, MRL1pr/lpr mice were not exposed to exogenous CpG-DNA, so the beneficial effect of G-rich DNA is compatible with the influence with endogenous CpG-DNA–mediated effects. Our data support the hypothesis that endogenous CpG-DNA–rich chromatin activates TLR-9–positive immune cells, specifically B cells, macrophages, and dendritic cells, and thus contribute to the pathogenesis of lupus. Apart from the experimental data in mice, this concept is also supported by the therapeutic properties of chloroquine, an unspecific blocker of endosomal TLR activation, in the treatment of human lupus (31). Our observation that administration of G-rich DNA attenuates the course of the lupus-like disease in MRL1pr/lpr mice also argues in favor of endogenous CpG-DNA fragments as pathophysiologic contributors to the murine disease and indicates G-rich DNA as a potential therapeutic pathway for the treatment of SLE.

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References


Figure 6. Serum dsDNA autoantibody levels and glomerular immune complex deposits in MRL1pr/lpr mice. Serum dsDNA autoantibody IgG1 (A) and IgG2a (B) levels were determined by ELISA (n = 8 to 10). Data are means ± SEM. *P < 0.05 versus saline. (C) Renal sections were stained for IgG1 and IgG2a, as indicated. Note less glomerular IgG1 and IgG2a deposits in ODN 2114–treated MRL1pr/lpr mice. Images are representative of 10 mice in each group. Magnification, ×400 in C.

Figure 7. B cell activation in MRL1pr/lpr mice. (A) B cells were isolated from MRL1pr/lpr mice as described in Materials and Methods. B cells were incubated with CpG-ODN, CpG-ODN plus different concentrations of ODN 2114, or standard medium without supplements for 72 h as indicated. B cell proliferation was assessed by CellTiter 96 proliferation assay. (B) B cells were isolated as before and incubated with LPS alone or LPS with different concentrations of ODN 2114 or standard medium without supplements for 72 h as indicated. Results are means ± SEM from one of two comparable experiments, each performed in duplicate.


