HIV-1 gp120 Impairs the Induction of B Cell Responses by TLR9-Activated Plasmacytoid Dendritic Cells

Nancy P. Y. Chung, Katie Matthews, Per Johan Klasse, Rogier W. Sanders and John P. Moore

*J Immunol* published online 24 October 2012
http://www.jimmunol.org/content/early/2012/10/24/jimmunol.1201905

Supplementary Material
http://www.jimmunol.org/content/suppl/2012/10/24/jimmunol.1201905.DC1

Why The JI?
- **Rapid Reviews!** 30 days* from submission to initial decision
- **No Triage!** Every submission reviewed by practicing scientists
- **Speedy Publication!** 4 weeks from acceptance to publication

*average

Subscription
Information about subscribing to *The Journal of Immunology* is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts

The Journal of Immunology is published twice each month by
The American Association of Immunologists, Inc.,
1451 Rockville Pike, Suite 650, Rockville, MD 20852
Copyright © 2012 by The American Association of Immunologists, Inc. All rights reserved.
Print ISSN: 0022-1767 Online ISSN: 1550-6606.
HIV-1 gp120 Impairs the Induction of B Cell Responses by TLR9-Activated Plasmacytoid Dendritic Cells

Nancy P. Y. Chung,* Katie Matthews,* Per Johan Klasse,* Rogier W. Sanders,*† and John P. Moore*

Plasmacytoid dendritic cells (pDCs) play a central role in innate and adaptive immune responses to viral infections, including HIV type 1 (HIV-1). pDCs produce substantial quantities of type I IFN and proinflammatory cytokines upon stimulation via TLRs, specifically TLR7 or TLR9. The HIV-1 envelope glycoproteins, exemplified by the gp120 monomer, are the focus of vaccines aimed at inducing B cell responses. We have studied how the interactions of gp120 with various receptors on human pDCs affect the activation of these cells via TLR9 and their subsequent ability to stimulate B cells. We observed that IFN-α production by pDCs in response to TLR9, but not TLR7, stimulation was reduced by exposure to gp120. Specifically, gp120 inhibited the CpG-induced maturation of pDCs and their expression of TNF-α, IL-6, TLR9, IFN regulatory factor 7, and BAFF. Receptor-blocking and cross-linking studies showed that these inhibitory effects of gp120 were mediated by interactions with CD4 and mannose-binding C-type lectin receptors, but not with the chemokine receptors CCR5 and CXCR4. Of note is that gp120 inhibited the activation of B cells by TLR9-stimulated pDCs. Taken together, our data show that HIV-1 gp120 impairs pDC functions, including activation of B cell responses, and imply that TLR9 ligands may not be good adjuvants to use in combination with envelope glycoprotein vaccines.

The Journal of Immunology, 2012, 189: 000–000.

The gp120 glycoprotein binds to several surface receptors on T and B cells, monocytes/macrophages, and dendritic cells (DCs), including CD4, chemokine receptors, and mannose-binding C-type lectin receptors (MCLRs) such as DC-specific ICAM-3–grabbing nonintegrin (DC-SIGN), DC immunoreceptor (DCIR), and blood DC Ag-2 (BDCA-2) (5–6). Interactions between gp120 and MCLRs may modulate immune cell functions. For example, gp120 binding to DC-SIGN modulates TLR signaling and activates the Raf-1 kinase–dependent acetylation of transcription factor NF-κB, which prolongs and enhances IL-10 transcription by DCs (7, 8). HIV-1 uses DC-SIGN, via gp120 binding, to facilitate the productive infection of DCs and also triggers TLR8 signaling via its ssRNA content (9). The mannose-dependent binding of gp120 to MCLRs can also trigger IL-10 production and impair the maturation of monocyte-derived DCs (10). Preventing gp120–MCLR interactions by removing mannose moieties from gp120 or using the blocking ligand griffithsin (GRFT) enhances anti-gp120 Ab responses in mice (11, 12). Finally, gp120 activates B cells to undergo Ig class switching through a CD40-independent pathway involving BAFF and MCLRs (13).

Plasmacytoid dendritic cells (pDCs) serve as a link between innate and adaptive immunity (14, 15). pDCs express the gp120 receptors CD4, CCR5, and CXCR4, as well as MCLRs including BDCA-2 and DCIR (5, 6). They also express TLR7 and TLR9, which recognize ssRNA and unmethylated DNA/synthetic CpG oligodeoxynucleotides (ODNs), respectively (15–18). TLR ligation activates pDCs to produce high levels of type I IFN, which has antiviral activity, as well as other cytokines such as TNF-α and IL-6 that activate NK cells, monocytes, B cells, and T cells (15). The roles played by pDCs during HIV-1 infection have been studied extensively; progressive infection is associated with a reduction in the number of pDCs and an impairment of their functions, such as a decrease in type I IFN secretion (19–22). In vitro studies have shown that pDCs produce substantial quan-

*Department of Microbiology and Immunology, Weill Cornell Medical College, New York, NY 10021; and Laboratory of Experimental Virology, Department of Medical Microbiology, Center for Infection and Immunity Amsterdam, Academic Medical Center, University of Amsterdam, 1105 AZ Amsterdam, The Netherlands

Received for publication July 10, 2012. Accepted for publication September 27, 2012.

This work was supported in part by National Institutes of Health Grant AI36082 (to J.P.M.). R.W.S. is a recipient of the Vidi grant from The Netherlands Organization for Scientific Research and a Starting Investigator Grant from the European Research Council (ERC-StG-2011-280829-SHEV).

Address correspondence and reprint requests to Dr. John P. Moore and Dr. Rogier W. Sanders, Department of Microbiology and Immunology, Weill Cornell Medical College, New York, NY 10021. E-mail addresses: jpm2003@med.cornell.edu (J.P.M.) and rws2002@med.cornell.edu (R.W.S.)

The online version of this article contains supplemental material.

Abbreviations used in this article: 7-AAD, 7-aminoactinomycin D; APRIL, a proliferation-inducing ligand; BDCA-2, blood dendritic cell Ag-2; C\(_t\), threshold cycle; DC, dendritic cell; DCIR, dendritic cell immunoreceptor; DC-SIGN, dendritic cell-specific ICAM-3–grabbing nonintegrin; Env, envelope glycoprotein; GRFT, griffithsin; HIV-1, HIV type 1; IRF-7, IFN regulatory factor 7; MCLR, mannose-binding C-type lectin receptor; mDC, myeloid dendritic cell; NAb, neutralizing Ab; ODN, oligodeoxynucleotide; pDC, plasmacytoid dendritic cell; sCD4, soluble CD4; WMPT, Wilcoxon matched-pairs test.

Copyright © 2012 by The American Association of Immunologists, Inc. 0022-1767/12/$16.00

www.jimmunol.org/cgi/doi/10.4049/jimmunol.1201905

Published October 24, 2012, doi:10.4049/jimmunol.1201905
pDCs regulate B cell differentiation and Ig production via IFN-α and IL-6 secretion. Thus, the release of IFN from pDCs triggers naive B cells to develop into plasmablasts, which become differentiated to Ab-secreting B cells in response to IL-6 (28). pDCs also promote the proliferation and differentiation of B cells that are stimulated by BCR cross-linking and TLR9 ligation in processes involving both soluble factors and cell-to-cell contact (29, 30). Other pDC-boosted events include the enhanced differentiation of TLR7/8-stimulated memory B cells, the IFN-α-mediated, T cell–dependent differentiation of naive B cells, and the TLR7-dependent, IFN-independent activation of naive B cells (31–33). At a mechanistic level, interactions between CD70 on pDCs and CD27 on memory B cells are what drive B cell growth and differentiation (34). Furthermore, pDCs and myeloid DCs (mDCs) both upregulate BAFF and a proliferation-inducing ligand (APRIL) expression via an IFN-mediated pathway (35, 36). The production of these two cytokines by pDCs is involved in the T cell–independent induction of IgA by B cells in GALT (36). Similarly, mDCs trigger CD40-independent Ig class switching in B cells through BAFF and APRIL (35). However, little is known about how exposure to gp120 affects pDC-mediated B cell growth and differentiation and hence how these cells respond to Env-based vaccines. CpG ODNs have adjuvant and immune-stimulatory properties that make them of interest for treating, or vaccinating against, allergy, cancer, and viral infections (37, 38). In this study, we have examined how exposure to gp120 affects the response of pDCs to CpG ODNs and the ability of the treated pDCs to subsequently stimulate B cell differentiation. We observed that CpG-induced pDC maturation, cytokine secretion, and TLR9, IFN regulatory factor 7 (IRF-7), and BAFF mRNA expression were all reduced by exposure to gp120. Furthermore, the addition of gp120 to cocultures of CpG-stimulated pDCs and B cells suppressed B cell proliferation, plasma cell differentiation, and Ig secretion. A better understanding of the various interactions among gp120, TLR activators, pDCs, and B cells may therefore guide improvements to adjuvant strategies for HIV-1 Env vaccines.

**Materials and Methods**

**Isolation of pDCs and B cells**

pDCs and B cells were isolated from buffy coats obtained from the New York Blood Center. pDCs were purified from human PBMCs using a CD304 (BDCA-4) Microbead Kit (Miltenyi Biotec). The purity of the enriched pDC population was >97% as assessed by CD123 and BDCA-2 staining. Total primary B cells were isolated from PBMC using the B cell Isolation Kit II (Miltenyi Biotec). pDCs and all B cell subsets were cultured in RPMI 1640 containing 10% FBS, 2 mM L-glutamine, 100 U/ml penicillin, 100 U/ml streptomycin, 1 mM sodium pyruvate, and 10 mM HEPES (all from Invitrogen). To inhibit gp120 binding to CD4, CCR5, CXCR4, and MCLRs on pDCs, they were incubated with anti-CD4 (clone 403-114; Miltenyi Biotec) or a matched isotype control (mouse IgG1) at 5 μg/ml and with or without anti-CXCR4 (clone 2G7) at 5 μg/ml for 20 min at 37°C, washed, and then cultured with CpG-B for 2 d. ELISAs were used to quantify the cytokine contents of cell supernatants.

pDCs were activated for 18 h with CpG-A (ODN 2216; Invivogen) at 70 μM, or the small-molecule CXCR4 ligand AMD3100 (Genzyme) at 1 μM, prior to addition of gp120 and CpG-B. Alternatively, gp120 was mixed with soluble CD4 (sCD4; Progenics Pharmaceuticals) at 10 μg/ml or the carbohydrate binding protein GRFT (Intruncept Biomedicine) at 20 nM for 1 h at room temperature before addition to the pDC culture. In cross-linking experiments, pDCs were incubated with an anti-BDCA-2 Ab (clone AC144; Miltenyi Biotec) or a matched isotype control (mouse IgG1, clone AC144) at 5 μg/ml for 30 min at 37°C, washed, and then cultured with CpG-B for 2 d. ELISAs were used to quantify the cytokine contents of cell supernatants.

**Real-time PCR**

Total RNA was isolated from pDC using the QiaGen RNeasy Kit (Qiagen). On-column DNase digestion was performed to remove contaminating genomic DNA according to the manufacturer’s instructions. Total RNA was reverse transcribed into cDNA. Briefly, secondary RNA structure was removed by heating for 5 min at 70°C. First-strand cDNA synthesis was carried out for 1 h at 37°C in 20 μl solution containing 25 μg/ml random primers, 0.5 mM 2′-deoxynucleoside 5′-triphosphate, 5 mM DTT, 40 U RNase Inhibitor, and 200 U murine Moloney leukemia virus reverse transcriptase in 1× murine Moloney leukemia virus reverse transcriptase. cDNA was then diluted and used for real-time PCR reactions to quantify TLR9 (assay ID: Hs00370913_m1), BAFF (assay ID: Hs00198106_m1), and APRIL (assay ID: Hs00601664_g1) in a 384-well plate. Each reaction was carried out in 10 μl solution containing 2× TaqMan reaction mix and 0.5 μl TaqMan FAM dye–labeled MGB probe using a 7900HT Fast Real-Time PCR machine (Applied Biosystems). Target gene expression was normalized against the level of GAPDH (assay ID: Hs99999905_m1). The threshold cycle numbers (Cₚ) values for ΔCₚ (CₚΔ = Cₚtarget gene − CₚGAPDH) were calculated and converted into arbitrary units using the formula: 2−ΔΔCₚ × 1000.

**pDC and B cell cocultures**

To examine how gp120-treated pDCs affected the regulation of B cell responses, an in vitro pDC–B cell coculture system was established. In this study, CpG-B was used because preliminary studies showed it to be the most potent B cell stimulator in this experimental system (Supplemental Fig. 1). Freshly isolated pDCs were treated with CpG-B (7 μg/ml) and gp120 (1 μg/ml) for 2 d before washing with complete medium to remove residual CpG-B and gp120. For coculture, 2 × 10⁶ B cells were added to 1 × 10⁵ pDCs in 96-well round-bottom plates in the presence of soluble Mega CD40L (200 ng/ml; Enzo Life Sciences), IL-2 (50 U/ml; National Institutes of Health AIDS and Reference Reagent Program), and IL-10 (10 ng/ml; R&D Systems). On days 0, 3, 5, and 7 of the coculture, the viability of the B cells was examined using Annexin V (7-AAD) (BD Biosciences) and CD19 staining followed by flow cytometry. The number of viable (7-AAD−) B cells was quantitated as a percentage of the total. To analyze B cell proliferation, the cells were pulsed with BrdU for 6 h on day 5 before BrdU incorporation was measured using a cell proliferation ELISA kit according to the manufacturer’s instructions (Roche Diagnostics). On day 7, cells from the coculture were collected, stained with CD20 (clone 2H7) and CD38 (clone HIT2), and analyzed using an LSR II flow cytometer (BD Biosciences). For analysis of IgA and IgM secretion by ELISA (Bethyl Laboratories), the cells were cocultured for 14 d before culture supernatants were collected.

**Statistical analysis**

Data are presented as the means ± SEM of independent experiments carried out using pDCs from different donors. We used nonparametric tests.
statistics throughout because too few data points were available to allow testing for Gaussian distribution. Blood-donor and other interexperimental variation meant that pairing of the data points might be effective. When pairing was effective (the correlation coefficient, r, ranged from 0.81 to 1, and the p values for the significance of the pairing ranged from 0.001 to 0.042), we performed Wilcoxon matched-pairs test (WMPT). In all other cases, we used the Mann–Whitney U test. Because all observed differences were in the predicted direction and variation in the opposite direction beyond control values could be considered random, we used one-tailed tests. The α level was set to 0.05. Statistical tests were performed in Prism 5.0d (GraphPad Software).

Results

**HIV-1 gp120 impairs CpG-induced IFN-α production by pDCs**

To examine the effects of gp120 on pDC function, the cells were treated with endotoxin-free recombinant proteins derived from the R5 strain JR-FL, the X4 strain MN, or the X4 strain IIIB in the presence of TLR9 agonists (CpG-B or CpG-A). In all of these studies, gp120 (JR-FL unless specified) was used at 1 μg/ml (8.3 nM); preliminary experiments showed that this concentration was sufficient to exert biological effects, and we wished to avoid possible toxic effects of higher amounts. By themselves, neither JR-FL nor MN gp120 induced IFN-α secretion from pDCs but both inhibited, by 30–73%, IFN-α secretion in response to CpG-B (JR-FL: p = 0.0043; MN: p = 0.0022) (Fig. 1A). The IFN-α response to CpG-A was also inhibited (JR-FL: p = 0.0043; IIIB: p = 0.0079) (Fig. 1A). In contrast, the HIV-1 p24 Gag protein had no inhibitory effect (p = 0.86, NS) (Fig. 1B). Furthermore, gp120 did not inhibit IFN-α production in response to TLR7 activation by R-848 at 1 μg/ml (p = 0.35, NS) (Fig. 1C). Hence, the gp120-mediated suppression of IFN-α production is specific for the TLR9 pathway. These observations are consistent with a prior report on how gp120 affects pDCs (5).

**gp120 inhibits CpG-B–induced pDC maturation**

Next, we examined how gp120 affected the TLR9-stimulated maturation of pDCs, as determined by upregulation of maturation markers (Fig. 2A). As expected, CpG-B induced pDCs to mature, but the presence of gp120 reduced the expression levels of various maturation markers: CD40 (by 46%; p = 0.0078, WMPT), CD83 (by 31%; p = 0.031, WMPT), and HLA-DR (by 34%; p = 0.014), all compared with stimulation with CpG-B alone (Fig. 2B). The reduction in CCR7 expression was of borderline significance (p = 0.063). By itself, gp120 did not affect the baseline expression level of any of the maturation markers (Fig. 2A). Similar results were obtained using CpG-A in place of CpG-B (Supplemental Fig. 2).

**gp120-mediated inhibition of IFN-α production involves CD4 and MCLRs**

We used saturating concentrations of inhibitors of gp120–receptor interactions to study the underlying mechanisms. Treating the pDCs with an anti-CD4 mAb or ligating gp120 with sCD4 both partially reversed (by 19–38%; p = 0.016, WMPT) the JR-FL gp120-mediated inhibition of IFN-α production, implying the gp120–CD4 interaction was involved. In contrast, the CCR5 and CXCRI4 ligands VCV and AMD3100 did not reverse the inhibitory actions of JR-FL and IIIB gp120s, respectively (Fig. 3A).

GRFT binds to the mannose moieties on gp120 and inhibits various interactions between this protein and MCLRs such as DC-SIGN, but it has no effect on gp120–CD4 binding (12, 39–41). GRFT also blocks HIV-1 from binding to DC-SIGN and the subsequent DC-SIGN–mediated transfer of the virus to CD4+ cells (42). We found that GRFT partially antagonized, by 16–28% (p = 0.016; WMPT), the inhibitory effect of gp120 on IFN-α production.
production (Fig. 3B), suggesting that a gp120–MCLR interaction is also involved in these events.

It has been shown that gp120 binds to BDCA-2, an MCLR expressed on pDCs (5). To study if BDCA-2 signaling triggers IFN-α production, we used a specific mAb (clone AC144) that activates this receptor by a cross-linking mechanism. The ligation of BDCA-2 by this mAb inhibited CpG-B–induced IFN-α production by 56% ($p = 0.016$, WMPT) (Fig. 3C). One possible implication is that the suppressive effects of gp120 on pDC function are mediated, at least in part, via binding to BDCA-2. We could not test this hypothesis directly, as although the BDCA-2 mAb blocks gp120 binding, it also itself activates signaling via this receptor. When the anti–BDCA-2 mAb was combined with gp120, there was a further suppression of the IFN-α response to CpG-B ($p = 0.016$, WMPT) (Fig. 3C). These findings suggest that the dual ligation of CD4 and BDCA-2 may have a synergistic inhibitory effect.

Together, our data suggest that gp120 binding to CD4 and MCLRs such as, but not limited to, BDCA-2 impairs the IFN-α response of pDCs to the TLR9 ligand CpG-B.
gp120 and BDCA-2 cross-linking downregulate IL-6 and TNF-α production in CpG-B–treated pDCs

In addition to IFN-α, pDCs produce other cytokines with antiviral or immune-stimulatory activities, including IL-6 and TNF-α. Both cytokines were induced by Cpg-B stimulation, and both responses were inhibited by gp120, albeit to different extents (IL-6 by 21%, p = 0.0076; TNF-α by 46%, p = 0.0087; Fig. 4A). The anti–BDCA-2 mAb reduced Cpg-B–stimulated production of TNF-α by 64% (p = 0.014), but had no effect on IL-6 (Fig. 4B). The receptor interactions of gp120 and the ligation of BDCA-2 by a mAb therefore cause similar, but not identical, impairments of pDC function. Moreover, different cytokines are affected in different ways.

gp120 and BDCA-2 cross-linking inhibit TLR9, IRF-7, and BAFF mRNA expression in Cpg-B–treated pDCs

TLR9 ligation on pDCs triggers an intracellular signaling cascade that activates IRF-7, which in turn regulates IFN gene transcription (43–45). Moreover, BAFF and APRIL expression in mDCs and pDCs are induced via the type I IFN signaling pathway (35, 36). In light of the suppressive effects of gp120 and the anti–BDCA-2 mAb described above, we used quantitative PCR to quantify TLR9, IRF-7, APRIL, and BAFF mRNA expression under similar conditions of Cpg-B stimulation, both in the presence and absence of gp120 (Fig. 5A, 5B). TLR9 expression was significantly reduced in response to Cpg-B, and the addition of gp120 further lowered its expression (by 28% compared with Cpg-B alone; p = 0.010). A different data pattern was seen with IRF-7 and BAFF mRNA in that Cpg-B markedly upregulated their expression, but markedly less so when gp120 was also present. Thus, the gp120–mediated reductions in IRF-7 and BAFF mRNAs were 45% (p = 0.014) and 42% (p = 0.0040), respectively (Fig. 5A, 5B). In contrast, Cpg-B induced APRIL expression, but gp120 had no suppressive effect (Fig. 5A, 5B). Finally, BDCA-2 cross-linking inhibited the expression of TLR9 (by 68%; p = 0.011), IRF-7 (by 56%; p = 0.0025), BAFF (by 51%; p = 0.0011), and APRIL (by 61%; p = 0.0011) in Cpg-B–treated pDCs (Fig. 5C). The responses to BDCA-2 cross-linking and gp120 were similar with the exception that APRIL mRNA was significantly reduced only by the former (Fig. 5B, 5C).

gp120 suppresses the B cell stimulatory capacity of Cpg-B–treated pDCs

As pDCs are potent stimulators of B cells, we examined how gp120 treatment affected the ability of TLR9-activated pDCs to drive B cell proliferation and differentiation. We used Cpg-B as the TLR9 ligand, as it is more potent than Cpg-A for B cell stimulation. Freshly isolated pDCs were treated with Cpg-B, with and without gp120, for 2 d and washed thoroughly prior to coculture with primary B cells; to mimic T cell help, CD40L, IL-2, and IL-10 were added to the cultures. The viability of CD19 B cells in cocultures with pDCs was examined by 7-AAD staining on days 0, 3, 5, and 7. Cell viability (untreated versus Cpg-B) was 91.3% versus 94.5% on day 0, 84.75% versus 91.8% on day 3, 80.2% versus 83.6% on day 5, and 76.1% versus 86.1% on day 7 (Supplemental Fig. 3). B cell viability in cocultures treated with Cpg-B and gp120 was comparable to that seen in cocultures given only Cpg-B. B cell proliferation was assessed on day 5 by measuring BrdU incorporation. Cpg-B treatment significantly increased the ability of pDCs to drive B cell proliferation, relative to untreated pDCs, but the boosting effect was substantially inhibited (by 63%; p = 0.0039, WMPT) when the pDCs were also exposed to gp120 (Fig. 6A).

To study differentiation to plasma cells, B cells were harvested from the coculture on day 7 and examined for plasma cell markers, as defined by a CD20–CD38lo phenotype. The presence of Cpg-B–treated pDCs in the coculture significantly increased the percentage of CD20–CD38lo plasma cells compared with untreated pDCs (32 versus 11% shown in the upper left quadrant of dot plot). The additional presence of gp120 reduced the plasma cell percentage by 76% (p = 0.0039, WMPT) (Fig. 6B).

Supernatants were collected from the cocultures on day 14 for quantification of IgG and IgM secretion. Cpg-B treatment of the pDCs increased by 3-fold the subsequent secretion of IgM and IgG by the B cells, as compared with untreated pDCs (967 versus 325 ng/ml for IgM; 1802 versus 622 ng/ml for IgG). The levels of both IgG and IgM were significantly reduced (by 84%, p = 0.0040; and...
75%, \( p = 0.0079 \), respectively) when gp120 was also present (Fig. 6C). Overall, these experiments show that gp120 inhibits the capacity of TLR9-triggered pDCs to activate B cells and drive their differentiation into Ig-secreting plasma cells.

**Discussion**

pDCs play an important role in the induction of innate and adaptive immune responses; they are potent producers of type I IFN, a cytokine with strong antiviral activity against viral infections (15).
TLR7 and TLR9, which recognize ssRNA and unmethylated DNA motifs, respectively, are the principal triggers of type I IFN production by pDCs (17, 18). A previous study found that HIV-1 gp120 inhibits TLR9-mediated pDC activation and cytokine production (5). In this study, we have further investigated how gp120 affects the functions of pDCs and the ability of these cells to drive B cell responses in vitro. We found that gp120 suppresses CpG-induced pDC maturation and cytokine production, which impairs the subsequent growth and differentiation of B cells.

The gp120 glycoprotein can bind to pDCs via the CD4, CCR5, and CXCR4 receptors, as well as via MCLRs such as BDCA-2 and DCIR (5, 6). We found that impeding gp120 binding to either CD4 or MCLRs partially reversed its inhibitory effect on IFN-α production, suggesting that both types of receptor are involved. Indeed, ligating both BDCA-2 and CD4 at the same time inhibited the IFN-α response to CpG-B synergistically. There are several reports that receptor cross-linking regulates IFN-α production by pDCs. For example, cross-linking CD4, BDCA-2, and BDCA-4 reduces their IFN response to HSV (46). Similarly, ligating BDCA-2 or DCIR inhibits CpG-induced IFN-α and TNF-α production (47–49). TLR9 ligands trigger the MyD88–IRF-7 signaling cascade, which leads to IFN secretion, a process in which IRF-7 plays an important role by initiating IFN gene transcription (45). In this study, we showed that the inhibitory effect of gp120 on the IFN-α response was associated with a reduction in IRF-7 mRNA expression. Overall, our observations suggest that gp120 binding to MCLRs and CD4 antagonizes TLR9-mediated signaling events that normally upregulate IFN-α production.

Several other viral proteins appear to have properties similar to HIV-1 gp120 in this regard. Thus, hepatitis B virus and its surface Ag and hepatitis C virus all inhibit IFN production in response to TLR9, but not TLR7, agonists (50–55). The IFN response of primary breast and ovarian tumor–associated pDCs to TLR9, but not TLR7, ligands was also impaired (56). Furthermore, pDCs from HIV-1–infected individuals express lower levels of IFN-α and IRF-7 mRNAs after exposure to TLR9 agonists when compared with cells from healthy people (57). The implication, again, is that TLR9 signaling is defective in these cells. A suggested explanation is that the interactions of viral proteins/components with immunoregulatory receptors such as MCLRs cause a reduction in TLR9 expression (56). Consistent with this hypothesis, we observed that gp120 and BDCA-2 ligation each reduced TLR9 mRNA expression in CpG-treated pDCs.

It has been well documented that pDCs regulate B cell differentiation and Ig secretion, both via soluble factors such as IFN-α, IL-6, and BAFF (28, 32, 33, 35) and through cell-to-cell contact (29, 30, 34). The production of IFN-α by pDCs enhances interactions between B cells and T cells, leading to the T cell–dependent differentiation of naive B cells into Ab-secreting cells (33). In addition, pDC–derived IFN-α enhances a T cell–independent B cell response to TLR7/8 stimulation (32). In this study, we found that gp120 suppressed IFN-α, IL-6, and TNF–α production in CpG–B–treated pDCs, impairments that may be sufficient to account for the reductions in B cell proliferation, differentiation and Ig secretion in the corresponding pDC and B cell cocultures. Type I IFN also upregulates the expression of two potent B cell stimulatory cyto- kines, BAFF and APRIL, in both pDCs and mDCs (35, 36). These two cytokines play an important role in B cell survival, activation, differentiation, and Ig class switching (58–60). We observed that CpG-B stimulated BAFF expression in pDCs and that this response was significantly reduced by gp120, partly contributing to the diminished capacity of the gp120-treated cells to activate B cell differentiation and Ig secretion.

There have been several studies on whether HIV-1 infection affects TLR agonist responsiveness. Thus, pDCs isolated from acutely and chronically infected individuals respond poorly to TLR9 ligands (61). An impaired responsiveness to TLR9 activation has also been observed in memory and naive B cells from infected people (62). Whether these various observations are attributable to suppression by gp120, either as a soluble or a viro- rion– or cell–associated protein, is unknown (63). Overall, HIV-1 infection perturbs many components of the immune system, including B cells [e.g., hypergammaglobulinemia and polyclonal B cell hyperactivation (64–67)]. B cell dysregulation during HIV-1 infection involves the induction of activation-induced cytidine deaminase, which is essential for Ig-class switch recombination and somatic hypermutation (68). Moreover, there are indirect effects of HIV-1 infection that perturb the B cell compartment. For example, viral RNA can trigger changes in pDC functions via TLR7/8, inducing high levels of IFN-α that stimulate B cell differentiation (26). The key point is that HIV-1 infection is a much more complex situation involving more stimulatory or suppressive factors than arises when Env proteins are used as vaccines, even when these proteins are mixed with adjuvants that interact with the TLR system (e.g., CpG ODNs that act via TLR9). Our focus in this study was to better understand what might happen in the vaccine context rather than considering HIV-1 infection. Our central conclusion is that gp120 binding to CD4 and MCLRs on pDCs could impair TLR9 signaling, leading to reduced production of IFN and BAFF and an impaired B cell response.

Our findings are consistent with several reports that gp120 can have immunosuppressive effects on immune cells such as DCs (10, 69, 70), and T cells (71–74). Paradoxically, gp120 has also been reported to be a superantigen initiating polyclonal Ab responses in VHS B cells (75–78). Finally, the binding of gp120 to MCLRs triggers B cells to undergo polyclonal Ig class switching in the presence of BAFF (13). It remains to be understood which, if any, of these various suppressive or stimulatory effects of gp120 are relevant after vaccination, when local Env concentrations may be particularly high (63).

In summary, we have shown that gp120 can suppress TLR9–mediated pDC functions, including their ability to stimulate B cell responses. Hence, CpG ODNs may be unsuitable adjuvants for use in an HIV-1 Env vaccine, with other TLR activators being a better choice. The quality of T cell responses was improved when mice were immunized with HIV-1 Env peptides in combination with TLR 2/6, TLR3, and TLR9 ligands (79). However, B cell responses were not assessed in this study. Although we have only tested gp120 monomers in the current study, the receptor interactions of soluble, trimeric forms of Env are gp120 dominated and may be at least qualitatively similar to those seen with the monomer.

Disclosures
The authors have no financial conflicts of interest.

References


Supplementary Figure Legends

Supplementary Figure 1. CpG-B is more potent at inducing Ig secretion in a pDC and B cell co-culture. Freshly isolated pDCs were incubated with CpG-A or CpG-B for 2 days before washing to remove residual ligands. A co-culture involving $2 \times 10^4$ B cells and $1 \times 10^4$ pDCs was established in 96-well round bottom plates. After 14 days of co-culture, culture supernatants were collected for quantification of IgM, IgG and IgA by ELISA.

Supplementary Figure 2. HIV-1 gp120 impairs CpG-A-induced pDC maturation. pDCs were treated with CpG-A in the presence or absence of JR-FL gp120 and stained with MAbs against CD83, CCR7 and HLA-DR. The expression of maturation markers on CpG-A and JR-FL gp120-treated pDCs, relative to CpG-A-treated pDCs, is shown. The data represent the mean values ± SEM obtained using pDCs from three individual donors.

Supplementary Figure 3. The viability of CD19$^+$ B cells in pDC and B cell co-cultures. On days 0, 3, 5 and 7 of the co-culture, the viability of the B cells was examined using 7-amino-actinomycin D (7-AAD; BD Biosciences) and CD19 staining, followed by flow cytometry. The number of viable (7-AAD$^-$) B cells was quantified as a percentage of the total.
Supplementary Figure 2

CD83

CCR7

HLA-DR

$p = 0.029$

$p = 0.050$

$p = 0.050$
Supplementary Figure 3

- untreated
- CpG-B
- CpG-B + gp120

Cell viability (%) vs. Day

Day

0 1 2 3 4 5 6 7

0 20 40 60 80 100