Induction of Human Dendritic Cell Maturation Using Transfection with RNA Encoding a Dominant Positive Toll-Like Receptor 4

Robin M. Cisco, Zeinab Abdel-Wahab, Jens Dannull, Smita Nair, Douglas S. Tyler, Eli Gilboa, Johannes Vieweg, Yehia Daaka and Scott K. Pruitt

*J Immunol* 2004; 172:7162-7168; doi: 10.4049/jimmunol.172.11.7162
http://www.jimmunol.org/content/172/11/7162

**References**

This article cites 33 articles, 17 of which you can access for free at:
http://www.jimmunol.org/content/172/11/7162.full#ref-list-1

**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
Induction of Human Dendritic Cell Maturation Using Transfection with RNA Encoding a Dominant Positive Toll-Like Receptor 4

Robin M. Cisco,* Zeinab Abdel-Wahab,† Jens Dannull,* Smita Nair,* Douglas S. Tyler,* Eli Gilboa,* Johannes Vieweg,*† Yehia Daaka,* and Scott K. Pruitt2*†

Maturation of dendritic cells (DC) is critical for the induction of Ag-specific immunity. Ag-loaded DC matured with LPS, which mediates its effects by binding to Toll-like receptor 4 (TLR4), induce Ag-specific CTL in vitro and in vivo in animal models. However, clinical use of LPS is limited due to potential toxicity. Therefore, we sought to mimic the maturation-inducing effects of LPS on DC by stimulating TLR4-mediated signaling in the absence of exogenous LPS. We developed a constitutively active TLR4 (caTLR4) and demonstrated that transfection of human DC with RNA encoding caTLR4 led to IL-12 and TNF-α secretion. Transfection with caTLR4 RNA also induced a mature DC phenotype. Functionally, transfection of DC with caTLR4 RNA enhanced allostimulation of CD4+ T cells. DC transfected with RNA encoding the MART (Melan-A/MART-1) melanoma Ag were then used to stimulate T cells in vitro. Cotransfection of these DC with caTLR4 RNA enhanced the generation of MART-specific CTL. This CTL activity was superior to that seen when DC maturation was induced using either LPS or a standard mixture of cytokines (TNF-α, IL-6, IL-1β, and PGE2). We conclude that transfection of DC with RNA encoding a functional signaling protein, such as caTLR4, may provide a new tool for studying TLR signaling in DC and may be a promising approach for the induction of DC maturation for tumor immunotherapy. The Journal of Immunology, 2004, 172: 7162–7168.

The maturation state of dendritic cells (DC) is critical for the induction of effector T cell function (1). Although human DC express a variety of receptors that participate in the induction of maturation, members of the Toll-like receptor (TLR) family are central to this process. Of the 10 described human TLRs, monocyte-derived DC predominantly express TLRs 2 and 4 (2, 3). LPS, an agent commonly used to induce DC maturation experimentally, mediates its effects by binding (along with soluble CD14 and MD-2) to cell surface TLR4 (4, 5). Intracellular signaling pathways, including NF-κB and p38 mitogen-activated protein kinase (MAPK), are then activated and DC maturation is induced (6–9). LPS-induced maturation has been shown to markedly enhance the ability of Ag-loaded DC to stimulate Ag-specific T cell responses in vitro (1, 10, 11). In addition, Pasare and Medzhitov (12) recently reported that stimulation of TLR4 on DC using LPS blocks the T cell inhibitory activity of regulatory CD4+CD25+ T cells. Blockade of such regulatory T cell (Treg) activity may be critically important for effective DC-based tumor immunotherapy. However, the clinical use of LPS to induce DC maturation for immunotherapy is prohibited by concerns over LPS-mediated toxicity as well as batch-to-batch variability.

RNA transfection is one method that has been shown to be effective for loading DC with tumor Ags. In both human and murine systems, in vitro and in vivo, tumor Ag RNA-transfected DC have been shown to stimulate antitumor effector T cell responses (13–16). We have previously demonstrated that when RNA is transfected into DC, the RNA is translated into protein that can be processed into peptides and presented in the context of HLA class I (16). Translation of the RNA into a functional protein is not necessary for Ag processing to occur and, in fact, misfolded and incompletely translated protein products may enhance antigenic peptide presentation (17). Transfection of DC with RNA encoding a functional protein might allow control of specific cellular pathways. However, the ability of transfected RNA to be translated into a functional signaling protein remains to be shown.

In this study, we created a constitutively active human TLR4 (caTLR4) and used RNA encoding this caTLR4 to transfect human monocyte-derived DC. Transfection of DC with caTLR4 RNA induced DC maturation that was comparable to that achieved using the current “gold standard” cytokine mixture of TNF-α, IL-6, IL-1β, and PGE2 (18). Specifically, transfection with caTLR4 RNA induced secretion of IL-12 and TNF-α, up-regulated the expression of the phenotypic markers of maturation, and enhanced the allostimulatory activity of the DC. Finally, we evaluated the ability of RNA-transfected DC to stimulate Ag-specific T cell responsiveness against the human melanoma Ag MART (Melan-A/MART-1) and found that caTLR4 RNA cotransfection enhanced the ability of HLA-A2+ MART RNA-transfected DC to generate MART-specific effector T cells.

Materials and Methods

Cell lines and reagents

HEK293 cells were obtained from the American Type Culture Collection (Manassas, VA) and maintained in RPMI 1640 plus 10% FCS. The cell
line 293-luc-xB, a stable transfectant of HEK293 containing an NF-xB-dependent luciferase reporter plasmid, was created by Lipofectamine-mediated DNA transfection followed by geneticin (Invitrogen, Carlsbad, CA) selection. TAP-deficient, HLA-A201/1 T2 cells were a gift from Dr. P. Cresswell (Yale University, New Haven, CT) and were maintained in serum-free AIM-V medium (Invitrogen). Melanoma cell lines DM6 (Melan-A/MART1+), Gap3 (anti-A3), and A11.1 (anti-A11) were derived from fresh surgical melanoma specimens and were gifts from Dr. H. Seigler (Duke University Medical Center, Durham, NC). Melanoma cell line 397mel (HLA-A1/25, MART+), GAP3 (anti-A3), and A11.1 (anti-A11) were obtained from the American Type Culture Collection. A purified mAb against HLA-A1 was purchased from One Lambda (Canoga Park, CA).

Monocyte-derived DC

Human DC were generated from adherent monocytes as previously described (16, 19). Briefly, PBMC were isolated by Ficoll gradient centrifugation of buffy coat lymphocytes purchased from the American Red Cross. A limited HLA-A phenotype was determined by flow cytometry of PBMC using HLA-specific mAbs. PBMC not immediately used for DC production were cryopreserved in 90% human AB serum (Valley Labs, Winchester, VA)/10% DMSO. Fresh (or thawed) PBMC were plated in tissue culture flasks in AIM-V serum-free medium. After a 2-hr plastic adherence step, nonadherent lymphocytes were gently washed away and adherent monocyte-derived nonadherent monocytes were then cultured in serum-free medium (X-VIVO-15; BioWhittaker, Walkersville, MD) supplemented with 1000 U/ml GM-CSF (Immunix, Thousand Oaks, CA) and 1000 U/ml IL-4 (R&D Systems, Minneapolis, MN). After 5–6 days in culture, the immature DC were used to confirm their DC phenotype and purity using two-color flow cytometry and a panel of mAbs specific for CD3 (T cells), CD14 (monocytes), CD19 (B cells), CD40 (DC), CD56 (NK cells), CD80 (monocytes and DC), CD86 (monocytes and DC), HLA-class I, HLA-class II, as well as isotype-matched control mAbs. Only DC cultures free of significant monocyte, B, T, or NK cell contamination were used for further studies.

DNA constructs

A chimeric caTLR4 construct consisting of the nerve growth factor receptor leader sequence fused to a FLAG epitope tag followed by a truncated TLR4 molecule was created using PCR cloning and standard molecular biology techniques. The truncation of human TLR4 was located between aa M620 and P621, creating a caTLR4 as described by Medzhitov et al. (5), based on a deletion analysis of the Drosophila Toll (20). The chimeric caTLR4 was inserted into a modified pcDNA3.1 plasmid (Invitrogen) (which contains a T7 promoter 5′ to the insert site) into which a 64-adenosine synthetic poly(A) tail segment had been inserted at the 3′ end of the multiple cloning site. The insert was confirmed by DNA sequencing. Western blotting of lysates from HEK293 cells transfected with the caTLR4 plasmid confirmed the generation of the chimeric caTLR4 protein. The plasmid used for the in vitro transcription of green fluorescent protein (GFP) RNA has been previously described (15, 16, 21). The plasmid encoding MART with an A27L aa mutation was created by overlapping PCR of cloned wild-type MART using primers containing the desired DNA mutation and confirmed by sequencing. Western blotting, and functional studies (22).

In vitro transcription of RNA

For the production of RNA, plasmid DNA was digested with the restriction enzyme SpeI at a site positioned at the 3′ end of the 64-adenosine segment of the modified pcDNA3.1 plasmid. After ethanol precipitation and resuspension in water, the digested DNA was used as template for in vitro RNA transcription using a commercial kit (mMessage machine; Ambion, Austin, TX). After DNase treatment, the resultant RNA was purified, quantitated, evaluated by MOPS-formaldehyde agarose gel electrophoresis to confirm product purity and full-length RNA, and then stored at −80°C until use. LPS levels of the in vitro-transcribed caTLR4 RNA were below detection level (<0.5 endotoxin units/ml), as determined by the Limulus amebocyte lysate assay (Associates of Cape Cod, Falmouth, MA).

In several experiments, caTLR4 RNA was digested with RNase I (New England Biolabs, Beverly, MA) according to the manufacturer′s instructions and then boiled. This RNAse-treated caTLR4 RNA was then used for electroporation of DC as described below.

DC transfection

Immature human DC were electroporated with RNA as previously described (16). Briefly, the immature DC were harvested and washed three times in cold PBS, then resuspended in cold Opti-MEM (Invitrogen) at 1–2 × 106/100 μl. Two hundred-microliter aliquots of cells were mixed in a 2-mm gap cuvette along with a total of 20 μg RNA. When a combination of two RNAs was used, 10 μg of each RNA was used. The cells and RNA were then subjected to 300 V for 500 μs in a square wave electrooporator (BTX, San Diego, CA). The electroporated DC were immediately transferred to tissue culture wells with fresh X-VIVO-15 medium containing IL-4 and GM-CSF. Control DC were electroporated with GFP RNA, which allowed for assessment of electroporation transfection efficiency using fluorescence microscopy.

Induction of DC maturation

Maturation agents were added to the DC culture medium −2–4 h after DC were electroporated with RNA. The maturation agents used included polycl (12.5 μg/ml; Sigma-Aldrich, St. Louis, MO), LPS (5 μg/ml; Sigma-Aldrich), or cytokine mixture (18) consisting of TNF-α (5 ng/ml), rhIL-1β (5 ng/ml), rhIL-6 (150 ng/ml; all from R&D Systems), and PGE_2 (1 μg/ml; Sigma-Aldrich).

Cytokine secretion

DC culture supernatants were harvested 24 and 48 h after transfection and stored at −20°C until use. IL-12 p70 levels and TNF-α concentrations were assessed using commercially available ELISA kits (R&D Systems).

Allosstimulatory capacity of RNA-transfected DC

To evaluate the ability of DC electroporated with caTLR4 RNA to stimulate CD4+ T cells, we performed allogeneic MLRs using RNA-electroporated DC as stimulators. In these experiments, DC were electroporated with RNA, and after 1 hr in culture, maturation stimuli were added as indicated. After an additional 3 h of incubation, the DC were washed and resuspended in medium and irradiated (3000 rad). Allogeneic CD T cells (1 × 10^6), isolated by magnetic bead separation (Miltenyi Biotec, Auburn, CA) from PBMC, were then stimulated at a 10:1 (responder:stimulator) ratio with the RNA-electroporated DC. After 4 days in culture, 1 μCi of [3H]thymidine (NEN, Boston, MA) was added to each well and incorporated radioactivity was measured after 16 hr using liquid scintillation counting. GFP RNA-electroporated DC were used to establish the baseline proliferation induced by immature electroporated DC. GFP RNA-electroporated DC treated with various maturation stimuli served as a positive control for the stimulation of T cell proliferation by mature DC. DC alone and T cells alone were used as negative controls.

In vitro T cell cultures

For T cell cultures, only DC from HLA-A2+ donors were used, as determined by flow cytometry of donor PBL using the anti-HLA mAbs. Approximately 4 hr after transfection, DC were added to autologous nonadherent lymphocytes (as a source of T cells) at a 1:10 (stimulator:responder) ratio in tissue culture medium consisting of RPMI 1640 plus 10%FCS supplemented with antibiotics and 10 μM 2-ME. IL-2 at 20 U/ml was added beginning on day 7 and then twice per week thereafter. Each T cell culture was restimulated with RNA-transfected DC at 7- to 10-day intervals for a total of three to four stimulations. As a positive control for maturation, we used our current standard regimen consisting of exposure of RNA-electroporated DC to cytokine mixture beginning 1 hr after transfection. After 4 hr in culture, DC were washed and added to the T cell cultures. As a negative control for maturation, DC were left untreated after MART transfection. The cells were then subjected to 300 V for 500 μs in a square wave electroporator. After 4 hi nculture, DC were washed and added to the T cell cultures. As a positive control for the stimulation of T cell proliferation by mature DC, DC alone and T cells alone were used as negative controls.

Evaluation of MART peptide/HLA-A2 tetramer-positive T cells

A PE-labeled class I HLA-A2 tetramer loaded with the Melan-A27L immunodominant peptide analog ELAGIGILTV, in combination with a FITC-labeled anti-HLA-A2 (G4-6, 5 μg/ml; BD Biosciences, San Jose, CA) and was used according to the manufacturer′s instructions. Staining was evaluated using a FACSCalibur (Becton Dickinson, San Jose, CA). A27L immunodominant peptide analog ELAGIGILTV, in combination with a FITC-labeled anti-HLA-A2 tetramer loaded with the Melan-A27L immunodominant peptide analog ELAGIGILTV, in combination with a FITC-labeled anti-HLA-A2 (G4-6, 5 μg/ml; BD Biosciences, San Jose, CA) and was used according to the manufacturer′s instructions. Staining was evaluated using a FACSCalibur (Becton Dickinson, San Jose, CA).

Ag-specific T cell IFN-γ release

In vitro-stimulated T cells were evaluated for Ag-specific effector function using an IFN-γ ELISPOT assay as previously described (16). This assay was performed at a stimulator:responder ratio of 1:10 in triplicate. T2 cells
loaded exogenously with either MART A27L peptide or M1 peptide (influenza matrix protein 1 HLA-A2-restricted immunodominant peptide GILGFVFTL, as a negative control) were used as targets. In addition, melanoma cell lines, previously HLA-typed and evaluated for MART expression, were used as targets. Plates were scanned and images were counted by an ImmunoSpot Series Analyzer (Cellular Technology, Cleveland, OH).

**Determination of cytotoxicity**

³¹Cr release assays were performed in triplicate using established methods as previously described (23). Percent specific lysis was calculated from the equation: (experimental release – spontaneous release)/(maximum release – spontaneous release (targets in medium)) × 100. Spontaneous release was <15% of maximum release. SDs for triplicate wells were <5%.

**Results**

**Construction and evaluation of caTLR4**

We wanted to demonstrate the functional consequences of transfecting cells with constitutively active chimeric TLR4. To generate a constitutively active molecule, we deleted the extracellular portion of TLR4 (aa 1–620) (5). This deletion was based on a mutational analysis of *Drosophila* Toll in which the deletion of the homologous portion of the molecule created a constitutively active Toll (20). After confirming the identity of our construct by DNA sequencing, we demonstrated that HEK293 cells transfected with this construct expressed a FLAG-tagged protein of appropriate molecular mass by Western blotting of cell lysates (data not shown). Transfection of HEK293 cells with the plasmid containing this caTLR4 construct led to the activation of NF-κB, demonstrating that our chimeric caTLR4 DNA encoded a functionally active protein (data not shown).

Although these transfection experiments using plasmid DNA showed that the caTLR4 plasmid DNA had constitutive NF-κB-activating activity, our main goal was to determine whether RNA transcribed from this plasmid DNA could be transfected into cells and be translated into a functionally active signaling protein. We therefore used the caTLR4 plasmid DNA as a template for in vitro RNA transcription and evaluated whether transfection with this caTLR4 RNA would activate NF-κB. For these experiments, we created a stable transfectant of HEK293 cells containing a NF-κB dependent luciferase reporter (293-luc-B). When 293-luc-B cells were transfected with caTLR4 RNA, NF-κB activation was induced (Fig. 1), thus confirming that transfected caTLR4 RNA was translated into a functional signaling protein.

Having shown that we could electroporate a cell line with caTLR4 RNA and generate a functional protein, we wanted to demonstrate activation of cellular signaling in human monocyte-derived DC. To this end, we transfected immature DC with caTLR4 RNA and used Western blotting of DC cell lysates to evaluate activation of p38 MAPK, a signaling pathway known to be important in DC maturation (7). As shown in Fig. 2, p38 MAPK was phosphorylated to a greater extent after transfection with caTLR4 RNA, compared with the control GFP RNA. As a positive control for maturation in these experiments, DC were exposed to poly(I:C), a synthetic analog of dsRNA known to mediate maturation via TLR3 (24). These results further demonstrate that transfected caTLR4 RNA is translated intracellularly within DC into a functional signaling protein. Our next step was to evaluate the consequences of transfecting DC with caTLR4 RNA with respect to DC maturation.

**Effect of caTLR4 RNA transfection on DC: phenotypic and functional analysis**

DC maturation was evaluated by phenotypic analysis of cell surface markers after transfection with caTLR4 RNA. Fig. 3 shows that transfection of DC with caTLR4 RNA induced surface expression of the maturation marker CD83 and stimulated increased surface expression of CD40 and of costimulatory molecules CD80 and CD86. Expression of these phenotypic markers of maturation in caTLR4 RNA-transfected DC was comparable, or superior, to that induced by cytokine mixture or LPS in DC transfected with control RNA. In addition, Fig. 3 also demonstrates that treatment of caTLR4 RNA with RNase abolished its maturation-inducing effects on the DC phenotype, indicating that the effects observed after caTLR4 RNA transfection were not due to LPS contamination. These results confirmed that transfection of DC with caTLR4 RNA induced phenotypic maturation of DC. The next step was to measure the functional consequences of caTLR4 RNA-induced DC maturation. Various parameters of DC function were examined, starting with cytokine secretion.

The effect of caTLR4 RNA transfection on DC cytokine secretion was determined by measuring cytokine levels in culture supernatants using ELISA. As shown in Fig. 4A, transfection with caTLR4 RNA induced the secretion of both IL-12 (p70) and TNF-α. As a control for DC maturation, we exposed the DC to either LPS or cytokine mixture. As demonstrated, DC transfected with caTLR4 RNA secreted TNF-α at levels comparable to those

**FIGURE 1.** RNA encoding caTLR4, when transfected into 293-luc-B cells, activates NF-κB. 293-luc-B cells were transfected with 293-luc-B cells (HEK293 cells stably transfected with a NF-κB inducible luciferase reporter gene) were transfected with either caTLR4 or GFP (negative control) RNA. After 6 h of serum starvation, luciferase activity was measured in cell lysates. TNF-α was added as indicated as a positive control for NF-κB activation. Data are shown as fold increase in luciferase activity above basal.

**FIGURE 2.** Transfection of DC with caTLR4 RNA activates p38 MAPK. Human DC were transfected with the indicated RNA and left untreated or were exposed to poly(I:C) (PIC) to induce maturation. Forty-eight hours later, cell lysates were prepared, subjected to SDS-PAGE, and analyzed for expression of phospho-p38 (P-p38) and total p38 by Western blotting. Equal amounts of total protein were loaded in each lane. Positive staining is seen for DC samples treated with poly(I:C) as well as for DC transfected with caTLR4 RNA. The results are representative of two experiments.
induced by LPS (Fig. 4A). Similarly, as shown in Fig. 4B, LPS treatment and caTLR4 RNA transfection of DC induced comparable levels of IL-12. Thus, consistent with functional DC maturation, electroporation of caTLR4 RNA into DC induced the secretion of immunostimulatory cytokines. When caTLR4 RNA digested with RNase was used for DC electroporation, the induction of TNF-α (Fig. 4C) and IL-12 (Fig. 4D) was abolished, confirming that the cytokine secretion induced by caTLR4 RNA transfection was not due to contaminating LPS.

We next wanted to assess the effect of caTLR4 RNA transfection on the ability of DC to stimulate helper T cells. We therefore evaluated the ability of RNA-transfected DC to stimulate proliferation of allogeneic CD4+ T cells. As demonstrated in Fig. 5, caTLR4 RNA-transfected DC were more efficient stimulators of T

---

**FIGURE 3.** Transfection of DC with caTLR4 induces phenotypic maturation. DC were transfected with the indicated RNA and then either left untreated or exposed to LPS or the cytokine mixture (CC) to induce maturation. Forty-eight hours later, DC were harvested and surface phenotype was evaluated by flow cytometry. These results are representative of four experiments.

**FIGURE 4.** Transfection of DC with RNA encoding caTLR4 results in IL-12 and TNF-α secretion. Immature monocyte-derived human DC were transfected with the indicated RNA and placed in culture. In some cultures, either the cytokine mixture (CC) or LPS was added as a maturation inducer. Forty-eight hours later, supernatants were harvested and levels of secreted TNF-α (A) and IL-12 p70 (B) were determined by ELISA. (GFP RNA = RNA encoding GFP used as a negative control). The results shown (A and B) are representative of eight experiments, each with similar results. The effect of RNase digestion on the ability of caTLR4 RNA transfection to induce DC cytokine secretion was also evaluated for TNF-α (C) and IL-12 p70 (D). The results shown (C and D) are representative of three experiments, each with similar results.
cell proliferation, when compared with DC transfected with GFP RNA. The stimulation of proliferation seen with caTLR4-transfected DC was comparable to and in some cases superior to that seen with DC stimulators matured with the cytokine mixture after transfection. In two additional experiments, the enhanced allostimulation observed for DC electroporated with caTLR4 RNA was abolished when the caTLR4 RNA was treated with RNase before electroporation (data not shown). This further confirmed that the effects observed after caTLR4 RNA transfection were not due to contaminating LPS. These results, along with the phenotype and cytokine secretion data, demonstrate that transfection of DC with caTLR4 RNA induced DC maturation that was comparable to or superior to that induced with the clinically used cytokine mixture or LPS.

A hallmark of mature DC function is the ability to stimulate naive CTLs, a function critical for generating antitumor immunity. We therefore evaluated whether transfection with caTLR4 RNA would enhance the ability of DC to stimulate an Ag-specific effector T cell response in vitro. T cells were stimulated with DC transfected with MART RNA, as a tumor Ag, and caTLR4 RNA. The highest levels of MART peptide-specific tetramer-positive CD8⁺ T cells were induced by MART RNA-transfected DC stimulators that were matured with caTLR4 RNA (Fig. 6 and Table I).

We further evaluated the function of DC transfected with MART RNA and caTLR4 RNA by measuring IFN-γ secretion and cytolytic activity of T cells stimulated with these DC. To measure IFN-γ secretion, we used the ELISPOT assay. DC transfected with MART RNA and caTLR4 RNA stimulated Ag-specific IFN-γ secretion at levels comparable to that induced by MART RNA-transfected DC stimulators matured with the cytokine mixture (Fig. 7). As shown, these T cells specifically recognized both T2 cells loaded with MART A27L peptide and DM6 cells, an HLA-A2⁺ MART⁺ melanoma cell line.

Finally, we wanted to assess the ability of the T cells stimulated with MART and caTLR4 RNA-transfected DC to lyse MART-expressing targets. As shown in Fig. 8, T cells stimulated with MART RNA-transfected DC and matured using caTLR4 RNA were the most effective at lysing target cell lines in a MART Ag-specific manner. These results suggest that the induction of DC maturation with caTLR4 RNA transfection is highly effective in stimulating the generation of Ag-specific effector T cells, and may be superior to maturation induced using the clinically utilized cytokine mixture or LPS.

**Discussion**

DC maturation is critical for effective stimulation of Ag-specific effector T cell responses (1). Experimentally, a variety of agents have been used to induce DC maturation, including monocyte-conditioned medium (25), cytokine mixture (consisting of TNF-α, IL-6, IL-1β, and PGE₂) (18), poly(I:C) (a synthetic analog of dsRNA) (24), CpG oligonucleotides (26, 27), and LPS (6). These latter three agents mediate their effects on target cells through binding to endogenous TLRs (TLR3, 9, and 4, respectively) (5, 24, 28, 29).

The use of LPS for the induction of DC maturation in clinical immunotherapy is unlikely because of toxicity (potentially leading to toxic shock) and batch-to-batch variability. However, using in
vitro and in vivo animal models, DC induced to mature using LPS and then loaded with MHC-restricted antigenic peptides are highly effective in stimulating Ag-specific T cell responses (1, 10, 11). By using caTLR4 RNA to induce DC maturation, we sought to stimulate the pathways that mediate the effects of LPS on DC without using this exogenous potentially toxic agent.

When LPS binds to TLR4, the adaptor molecules myeloid differentiation factor 88, Toll-IL-1R domain-containing adapter protein/myeloid differentiation protein 88 adapter-like, and Toll-IL-1R domain-containing adapter inducing IFN-β are recruited to the intracellular Toll-IL-1R domain of TLR4, leading to activation of multiple signaling pathways, including NF-κB and p38 MAPK (30). Using inhibitors of these signaling pathways, Ardesha et al. (6) showed that both are critically important for optimal DC maturation by LPS. As demonstrated in Figs. 1 and 2, transfection of cells with caTLR4 RNA activates both NF-κB and p38 MAPK, similar to the known effects of LPS on intracellular signaling.

The ability of LPS-matured DC to generate effector T cells may in part be mediated by LPS-induced IL-12 secretion. IL-12 has been demonstrated to stimulate Th cell proliferation and is vital for the generation of Th1 responses (31, 32). As seen in Fig. 4, DC transfected with caTLR4 RNA secreted IL-12 at levels comparable to those achieved after exposure to LPS, demonstrating that our RNA construct is equal in potency with respect to this LPS-induced effect. When compared with the cytokine mixture used clinically to induce DC maturation, caTLR4 RNA transfection was superior to the cytokine mixture in inducing secretion of both IL-12 and TNF-α.

An additional mechanism by which LPS-treated DC may function to more effectively induce Ag-specific effector T cell responses is by promoting expansion of Th cells and biasing the Th response toward Th1. As assessed by the ability to stimulate proliferation of allogeneic CD4+ T cells, DC transfected with caTLR4 were comparable, or even superior, to DC transfected with control RNA and then matured using either LPS or cytokine mixture (Fig. 5).

LPS may also enhance the ability of DC to stimulate Ag-specific T cells through the inhibition of Treg. Pasare and Medzhitov (12) recently demonstrated that ligation of TLR4 (using LPS) or TLR9 (using CpG oligonucleotides) in a murine model reversed the ability of CD4+CD25+ Treg to inhibit CD4+ T cell proliferation. We are currently investigating the ability of caTLR4 RNA-transfected human DC to overcome the effects of Treg in vitro.

Although DC transfection with caTLR4 RNA clearly induces maturation, one of our most important findings is that MART RNA-transfected DC, when matured using caTLR4 RNA transfection, are superior inducers of anti-MART effector T cells. When compared with the use of cytokine mixture as a maturation inducer, caTLR4 RNA-transfected DC stimulated the generation of higher numbers of MART-specific effector T cells as assessed by both tetramer binding (Fig. 6 and Table I) and IFN-γ secretion (Fig. 7). In

![FIGURE 7. IFN-γ ELISPOT of T cells stimulated with DC transfected with MART and TLR4 RNA. Autologous T cells were serially stimulated with DC transfected with the indicated combinations of RNA. As a positive control for maturation induction, RNA-transfected DC were treated with cytokine mixture (CC) before being added to T cell cultures. After three serial stimulations, IFN-γ ELISPOT was performed using melanoma cell line targets DM6 (MART+, A2+) and 397mel (A3+, A2+, MART+) as well as T2 cells loaded with either the HLA-A2-restricted immunodominant MART A27L peptide or influenza M1 peptide (as a negative control). These results are representative of four experiments.](https://www.jimmunol.org/)

<table>
<thead>
<tr>
<th>DC treatment</th>
<th>A27L RNA + GFP RNA (%)</th>
<th>A27L RNA + GFP RNA + Cytokine Mixture (%)</th>
<th>A27L RNA + caTLR4 RNA (%)</th>
<th>Fold Increase over Cytokine Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.62</td>
<td>5.6</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.1</td>
<td>0.7</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>0.46</td>
<td>0.45</td>
<td>0.63</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>ND</td>
<td>0.01</td>
<td>1.7</td>
<td>170</td>
</tr>
<tr>
<td>5</td>
<td>ND</td>
<td>0.12</td>
<td>0.89</td>
<td>7.4</td>
</tr>
</tbody>
</table>

*The effector T cell populations generated after serial stimulation with RNA-transfected DC were stained with a MART peptide-loaded HLA-A2 tetramer. MART peptide-specific CD8+ T cells were then identified using flow cytometry. The percentages indicate the fraction of tetramer-positive cells within the entire population of T cells.

![FIGURE 8. MART Ag-specific lytic activity of T cells stimulated with caTLR4-transfected DC. After three serial stimulations with DC transfected with the indicated RNA, T cells were evaluated for Ag-specific lytic activity using a 51Cr release assay. Targets included melanoma cell lines DM6 (MART+, A2+), DM150 (MART+, A2+), and DM150 loaded with MART A27L peptide, as well as T2 cells loaded with either MART A27L peptide or influenza M1 peptide (as a negative control). These results are representative of three separate experiments, each with similar results.](https://www.jimmunol.org/)
addition, T cells stimulated with DC transfected with MART RNA and induced to mature using caTLR4 RNA transfection had the highest lytic activity against melanoma cells expressing MART (Fig. 8). Thus, the induction of DC maturation using caTLR4 transfection might have potential clinical applications for the stimulation of anti-tumor effector T cell responses during immunotherapy.

The use of caTLR4 RNA transfection to induce DC maturation has several additional practical advantages with respect to clinical applications for DC-based tumor immunotherapy. First, RNA transfection using electroporation is a simple procedure that eliminates the need for potentially toxic transfection reagents (such as lipid modifi ers) that have not been approved for clinical use. Second, RNA encoding tumor Ags can be cotransfected, along with lipid modifi es to minimize the need for potentially toxic transfection reagents (such as lipid modifi ers) that have not been approved for clinical use. Thus, the induction of DC maturation using caTLR4 RNA transfection avoids the signifi cant expense of purchasing clinical-ready recombinant human cytokines.

The use of constitutively active signal molecule RNA also has potential applications for more fully elucidating the role of specifi c TLRS in the induction of DC maturation. Constitutively active forms of several other TLRs that we are currently developing will be ideal for this purpose. As an example, dsRNA, the ligand for TLR3, has many additional effects on cellular signaling that are not mediated directly through binding to TLR3 (33). An RNA encoding a constitutively active TLR3 will allow us to specifi cally evaluate and manipulate dsRNA-mediated maturation-inducing effects in DC that are TLR3 mediated. In summary, we show that transfection of human monocyte-derived DC with caTLR4 RNA induces DC maturation. Both phenotypically and based on cytokine secretion, as well as ability to stimulate the terminal maturation of human dendritic cells. Drosophila embryo.

References