Fast Dendritic Cells Stimulated with Alternative Maturation Mixtures Induce Polyfunctional and Long-Lasting Activation of Innate and Adaptive Effector Cells with Tumor-Killing Capabilities

Chiara Massa and Barbara Seliger

*J Immunol* published online 27 February 2013
http://www.jimmunol.org/content/early/2013/02/27/jimmunol.1202024

**Supplementary Material**
http://www.jimmunol.org/content/suppl/2013/02/27/jimmunol.1202024.DC1

**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
Fast Dendritic Cells Stimulated with Alternative Maturation Mixtures Induce Polyfunctional and Long-Lasting Activation of Innate and Adaptive Effector Cells with Tumor-Killing Capabilities

Chiara Massa and Barbara Seliger

The clinical usage of dendritic cells (DC) for tumor immunotherapy still requires improvements. In this study, three alternative maturation mixtures were compared with the cytokine-based gold standard, and the overall interaction of the resulting DC with effector cells from the innate as well as the adaptive immunity was evaluated in healthy donors. Stimulation with the TLR-4 ligand monophosphoryl lipid A together with IFN-γ (alt-2 DC) resulted in DC with the highest levels of costimulatory molecule expression and IL-12p70/IL-10 ratio. Whereas all alternative DC were able to induce NK and γδ T cells to acquire cytotoxic properties and secrete type 1 and proinflammatory cytokines, after both short (20-h)- and long (5–8 d)-time coculture, secretion of IFN-γ by the innate populations was induced in response to alt-2 and alt-1 DC (TNF-α, IFN-γ, IL-1β, poly IC), but not to alt-3 DC (TNF-α, IFN-γ, IL-1β, CI097). Regarding CD8+ T cell–mediated Ag-specific immune responses, a heterogeneous pattern of responses was obtained among the healthy donors, suggesting rather a competition than a synergy among the different effector cells. Our data promote further evaluation of alt-2 fast DC for translatability into clinical immunotherapy trials, while also fostering the need to identify biomarkers for immune cell responsiveness and tumor susceptibility to be able to select for each patient the best possible DC-based therapy. The Journal of Immunology, 2013, 190: 000–000.

Dendritic cells (DC) are considered the most potent APCs of the immune system and have been investigated to employ their adjuvant activity in tumor immunotherapy. Clinical trials in different tumor entities have revealed safety and tolerability of such treatment. However, despite a frequent vaccine-induced expansion of precursor cells in the blood and/or the induction of delayed-type hypersensitivity, the rate of objective clinical responses obtained in tumor patients is very limited (1, 2). For this reason, an optimization of the protocol for vaccine DC production as well as their deep functional characterization is urgently needed to improve their clinical implementation.

The major protocol currently used for the production of vaccine DC is a two-step process, in which monocytes are first differentiated toward immature DC by a 5-d culture in the presence of GM-CSF and IL-4 (3), followed by their stimulation with the so-called gold standard cytokine mixture composed of TNF-α, IL-1β, IL-6, and PGE2 (4). The major disadvantages of this protocol are the labor- and time-consuming procedures together with an impaired secretion of the bioactive IL-12p70 that is critical for the induction of a type 1–oriented, cell-mediated immune response (5, 6). Therefore, alternative protocols for a faster differentiation of monocytes (7, 8) and a better maturation toward vaccine DC (9–12) have been developed during the last decade.

Despite the fact that the major aim of vaccination is the induction of a CD8+ T cell–mediated, Ag-specific immune response, innate effector cells have recently rekindled interest. NK, NK-T, and γδ T cells have been frequently defined as a first line of response, exhibiting cytotoxic capabilities that do neither require previous stimulation nor develop into memory cells. During the last years, this minimalistic view was altered due to the increased knowledge about the cross-talk between cells from the innate and adaptive immunity, indicating that innate effectors can also provide a helper role influencing the outcome of the adaptive immunity (13). For example, NK cells have been functionally and phenotypically dissected into two different subsets, the cytokotoxic NK cells characterized by a dim expression of the CD56 marker and positivity for CD16 (CD56dimCD16+) and a CD16-negative CD56bright (CD56+CD16−) cytokine producer subset (14). Moreover, murine models of viral infection as well as immunomonitoring of infected humans suggest that NK cells might develop memory-like properties and can thus provide stronger and quicker responses at a second encounter (15–17).

Based on these data, the potency of newly proposed protocols for vaccine DC should be evaluated regarding the adaptive and innate immunity. Therefore, a comparative analysis of the effects of different maturation mixtures on the interactions of fast DC with the different immune cell populations of the human blood was performed.

Materials and Methods

Maturation stimuli, Abs, and ELISA kits

Monophosphoryl lipid A (MLA) and the imidazoquinoline compound CI097 were purchased from InvivoGen (San Diego, CA), IL-1β from BioSource International (Camarillo, CA), IFN-γ from ProSpec (Reho-
DC OPTIMIZATION FOR INNATE AND ADAPTIVE ACTIVATION

voltage, Israel), IFN-γ from Immunotools (Friesoythe, Germany), polyinosinic: polycytidylic acid (polyIC) and PGE2, from Sigma-Aldrich (St. Louis, MO), TNF-α from PeproTech (Hamburg, Germany), whereas IL-6 was a gift of S. Rose-John (Institute of Biochemistry, University of Kiel, Kiel, Germany).

The following Abs were used: Alexa Fluor700 anti-CD3, eFluor450 anti-CD8a, PE-Cy7 anti-CD14, FITC anti-CD80, FITC anti-CD83, PE anti-CD86 (from eBioscience/Nat Tec, Frankfurt, Germany), PE anti-CD40, FITC anti-CD60, PE-Cy7 anti-CD80, PE-Cy7 anti-CD86, allophycocyanin Alexa Fluor750 anti-CD16 (from Beckman Coulter, Brea, CA), FITC anti-granzyme B, FITC and PerCP anti-V52, allophycocyanin anti-CD107a (from BioLegend, San Diego, CA), PE anti-CD69, and allophycocyanin anti-CD25 (from Becton Dickinson [BD] Biosciences, Franklin Lakes, NJ).

A minimum of 10,000 events gated on live, propidium iodide–negative cells was acquired either on a FACSscan (BD Biosciences) or a Navios (Beckman Coulter) flow cytometer and evaluated using CellQuest (BD Biosciences) or Kaluza (Beckman Coulter) software. The general gating strategy for the flow cytometric acquisition is shown in Fig. 1.

Concentration of IL-12p70 and IL-10 in DC supernatants was evaluated using commercially available ELISA kits (BioLegend and Immunotools, Friesoythe, Germany, respectively). For lymphocyte characterization, IFN-γ and TNF-α secretion were evaluated using the secretion assay kit from Miltenyi Biotec (Bergisch Gladbach, Germany), whereas the cytokine content of the culture supernatants was evaluated by means of the flowcytomix Th1/Th2/Th9/Th17/Th22 kit from eBioscience/Nat Tec following manufacturer’s instructions.

DC differentiation and maturation
Buffy coats from HLA-A–typed healthy donors were obtained from the blood bank of the University Hospital in Halle upon written informed consent. PBMCs were purified by a density gradient centrifugation on a Pansorbin layer (Pan-Biotec, Aidenbach, Germany), and then monocytes were isolated using anti-CD14–conjugated microbeads (Miltenyi Biotec). Differentiation was performed by seeding 10^6 cells/ml in serum-free CellGro medium (CellGenix, Freiburg, Germany) with 200 ng/ml GM-CSF (Leukine; Bayer HealthCare, Seattle, WA) and 1000 U/ml IL-4 (Immunotools) for 24–36 h to obtain fast DC. Maturation was induced by 18-h incubation in the presence of the gold standard (TNF-α + IL-1β + IL-6 + PGE2) and the three alternative mixtures, alt-1 (also known as α-type one polarizing; TNF-α + IL-1β + IFN-α + IFN-γ + polyIC) (10), alt-2 (MPLA + IFN-γ) (11), and alt-3 (TNF-α + IL-1β + IFN-γ + CL097; adapted from Ref. 12). The concentrations used in the maturation mixtures were as follows: CL097, 5 μg/ml; IFN-α, 3000 U/ml; IFN-γ, 500 U/ml; IL-1β, 5 ng/ml; IL-6, 5 U/ml; MPLA, 4 μg/ml; PGE2, 1 μM; polyIC, 1 μg/ml; M; TNF-α, 100 ng/ml.

At the end of the maturation period, supernatants were frozen for cytokine evaluation by ELISA, whereas DC were thoroughly washed and used for functional characterization (coculture assays).

DC lymphocyte coculture
All cocultures were performed in serum-free X-vivo15 medium (Lonza, Basel, Switzerland), using as effector cells the autologous PBMCs corresponding to the fraction of PBMCs remaining after CD14+ monocyte purification. When specified, CD8+ T cells were purified and CD56+ cells were depleted using microbeads following manufacturer’s instructions (Miltenyi Biotec).

For short-term cultures (4–21 h), 4 × 10^3 DC/well were seeded in U-bottom 96-well plates with 10^6 PBL in 200 μl, whereas for long-time culture (5–10 d), 10^3 DC were incubated with 10^6 PBL in 1 ml in 24-well plate.

For mechanisms evaluation, DC were preincubated with blocking Abs directed against IL-12p (35±70) (Gen-probe, San Diego, CA) for 30 min at 37°C before lymphocytes were added; the mAb concentration in the final volume was 10 μg/ml.

For evaluation of Ag-specific immune responses, mature DC were pulsed with synthetic peptides for 2 h at 37°C before incubation with effector cells for 10 d. To evaluate the expansion of naive CTL, the MelanA/Mart-1 peptide (AAAGIGITLV; Peptides & Electphants, Potsdam, Germany) was used due to the high frequency of MelanA/Mart-1 precursors in healthy donors (18). In such cases, purified CD8+ T cells were purified, total, or NK-depleted PBL were incubated with peptide-pulsed DC, and 50 μ/ml IL-2 (Prolien; Proleukin; Lilly, Indianapolis, IN), whereas for long-time culture (5–10 d), 10^3 DC were incubated with 10^6 PBL in 1 ml in 24-well plate.

For the statistical analysis, differences between treatments were evaluated using the one-way ANOVA test for correlated samples and the Tukey honestly significant difference (HSD) test performed with the web-based software Vassarstat (http://vassarstats.net). Significance upon Ab treatment and between CD8+ T cells and total PBL was evaluated using the two-tailed paired t test. Probabilities below 0.05 (*) or 0.01 (**) were considered significant. Data from different experiments are shown as mean ± SE, whereas SD among duplicate/triplicate wells are shown within single experiments.

Results
Characterization of mature fast DC
Monocytes were differentiated toward DC with the so-called fast DC optimization protocol and stimulated for 18 h with the gold standard and three alternative maturation mixtures, named alt-1, alt-2, and alt-3 (see Materials and Methods for composition). In response to all maturation mixtures, fast DC upregulated the expression of the co-stimulatory and adhesion molecules CD40, CD54, CD80, CD83, and CD86 (Figs. 1, 2A), but to a different extent. Among the alternative mixtures, alt-2 induced the highest expression levels.

Proliferation assay
Autologous PBL were labeled with 5 μM CFSE ( Molecular Probes, Invitrogen, Paisley, U.K.) or cell proliferation dye eFluor670 (eBioscience/Nat Tec) for 10 min at 37°C in PBS supplemented with 10% FCS (Invitrogen, Karlsruhe, Germany) and then thoroughly washed. A total of 10^6 PBL was added at a 10:1 ratio to mature DC for 5 d before the proliferation was evaluated by flow cytometry as dye dilution in gated lymphocyte subpopulations. One replicate well was used for determination of the absolute cell count upon the addition of Flow-Count Flurospheres (Beckman Coulter). The absolute counts of the different immune populations were obtained by combining the absolute total cell count from the evaluation with the beads and the percentages of the different subsets obtained upon counter staining with the different Abs.

Evolution of cytotoxicity
Development of cytotoxic activity was evaluated both in a standard [ 31Cr] release assay (day 5–10 cocultures) and by means of a CD107a degranulation assay (overnight and day 5–20 cocultures). Target cells to evaluate innate effector killing were Daudi cells, whereas the HLA-A2+ and A3+ melanoma cell line Mel1379 was used to evaluate Ag-specific killing upon peptide pulsing. As further controls for the Ag specificity in the MelanA/Mart-1 setting peptide-pulsed T2 cells and the undifferentiated HLA-A2+ melanoma cell line Na 8 that lack the expression of MelanA/Mart-1 were employed. The HLA-A2–restricted tyrosinase epitope p351 (YMNGTMSQV) was used as an unrelated Ag to pulse T2 cells.

For the [ 31Cr] release assay, labeled cells were incubated with titrated amounts of effector cells for 4 h before supernatants were collected for measurement in a gamma counter. Lysis was calculated as 100 × (experimental release − spontaneous release)/(maximum release − spontaneous release), where the maximum and spontaneous release were obtained by culturing the target cells in 1% Triton X-100 (Sigma-Aldrich) and X-vivo15 medium, respectively.

For the CD107a degranulation assay, 10^6 PBL were incubated 1:1 with target cells for a total of 4 h and the CD107a mAb was added after the first hour of culture. At the end of the incubation time, the various immune cell populations were stimulated by using Ab specific for CD3, CD8α, CD16, CD56, and V62 and counter stained with propidium iodide (Sigma-Aldrich). To evaluate the content of granzyme B, PBL were first stained with the live/dead fixable dead cell stain kit (Molecular Probes, Invitrogen, Paisley, U.K.) and the Ab for surface marker, then fixed in 4% paraformaldehyde, permeabilized in 0.01% saponin, and stained with a FITC-conjugated anti-granzyme B mAb or isotype control Ab.

Statistical analysis
Differences between treatments were evaluated using the one-way ANOVA test for correlated samples and the Tukey honestly significant difference (HSD) test performed with the web-based software Vassarstat (http://vassarstats.net). Significance upon Ab treatment and between CD8+ T cells and total PBL was evaluated using two-tailed paired t test. Probabilities below 0.05 (*) or 0.01 (**) were considered significant. Data from different experiments are shown as mean ± SE, whereas SD among duplicate/triplicate wells are shown within single experiments.
of these molecules, whereas alt-3 induced the lowest levels, which were for CD83 and CD86 even lower than that of the gold standard.

In line with published results, all alternative mixtures employed were able to induce the secretion of the bioactive IL-12p70 during DC maturation, whereas the gold standard induced no or very low levels of this cytokine (Fig. 2B, left). Furthermore, alt-1 and alt-3 induced high levels of IL-10 that were absent in the supernatants of gold standard and alt-2 DC (Fig. 2B, right). Upon reseeding in the absence of exogenous stimuli, the alt-1 and alt-2 DC were still able to secrete significant, but much lower levels of IL-12, whereas alt-1 DC also maintained a significant IL-10 secretion (Fig. 2C). Interaction with autologous PBL was able to induce IL-
12 secretion by alt-1 and alt-2 DC both when occurring immediately after maturation and after 24 h, during which the DC were left untreated (Fig. 2D), a setting mimicking the time required by vaccine DC for migration to the lymph node upon in vivo injection.

Alternative DC strongly stimulate innate cells in short-time culture

To analyze the functional properties of the various preparations, DC were incubated overnight (16–21 h) with autologous lymphocytes, and the culture supernatants were evaluated for the presence of cytokines corresponding to the different types of immune polarization, namely proinflammatory (IL-6 and TNF-α), type 1 (IL-1β, IL-2, and IFN-γ), type 2 (IL-4, IL-5, IL-10, and IL-13), type 9 (IL-9), type 17 (IL-17A), and type 22 (IL-22) cytokines. A potent secretion of IL-1β, IL-6, IFN-γ, and TNF-α was found in response to the coculture with the alternative DC, with alt-1 and alt-2 inducing higher levels than alt-3 DC, whereas almost no cytokines were detected in response to stimulation with gold standard DC. Regarding the other tested cytokines, only IL-10 was consistently detected among different donors and significantly produced uniquely in response to alt-1 DC (Fig. 3A). To dissect the responsible immune cell population(s), a cytokine secretion assay was performed and immune cells were then counterstained with CD3, CD56, and Vß2 Abs to identify NK (CD3-CD56+ and γδ T cells (CD3-Vß2+) following the gating strategy illustrated in Fig. 1. Despite the highly variable frequencies in the different donors, NK and γδ T cells responded to the overnight incubation with the alternative DC by secreting IFN-γ and TNF-α (Fig. 3B). A consistent secretion of IFN-γ by the innate populations was observed already after 4-h incubation with the alt-1 and alt-2 DC (Fig. 3C). Further staining with the CD16 Ab to dissect NK cell subsets revealed that both the CD56brightCD16+ and CD56dimCD16− subpopulations secreted IFN-γ after 4 (Fig. 3D) as well as after 16 h (data not shown).

Overnight stimulation with the alternative DC also resulted in the upregulation of activation markers like CD25 and CD69 (Supplemental Fig. 1) as well as in the induction of cytolytic functions. Indeed, innate cells stimulated with the alternative DC displayed an enhanced degranulation in response to Daudi cells in comparison with gold standard–stimulated effectors (Fig. 4A). Concerning the NK cell subpopulations, not only the CD56dimCD16+ population, but also the CD56brightCD16− cells were induced by alt-1 (data not shown) and alt-2 DC to degranulate upon incubation with Daudi cells (Fig. 4B, top and center). Intracellular staining revealed a dramatic induction of granzyme B in the CD56brightCD16− NK population by alt-1 (data not shown) and alt-2 DC (Fig. 4C, top), suggesting that their degranulation could also be associated with target killing. In contrast, in CD56dimCD16+ NK and γδ T cells, the already high expression of granzyme B was not significantly augmented by stimulation with the alternative DC (Fig. 4C, center and bottom).

Regarding the γδ T cell population, a highly donor-dependent expression of the CD56 marker, ranging from 0–50% of positive cells, was found (data not shown). Its expression did not strictly correlate with the effector function, because the frequency of degranulation was comparable in both CD56-positive and -negative cells, or was even slightly more pronounced in the negative subset (Fig. 4C, bottom).

Alternative DC have long-time effects on innate cells

Interaction between alternative DC and innate cells also had long-term consequences, as follows: an enhanced proliferation of innate cells was demonstrated by staining of lymphocytes with a prolifer-

FIGURE 3. Alternative DC induce cytokine secretion from innate lymphocytes. Mature DC were thoroughly washed and seeded with autologous total PBL in X-vivo 15 medium for 16–21 (A, B) or 4 h (C, D). At the end of the incubation, supernatants were collected and evaluated for the concentration of cytokines corresponding to the different immune polarization using multiplex technology (A), whereas lymphocytes were washed and evaluated for production of IFN-γ and TNF-α by means of a cytokine secretion assay (B–D) using the gating strategy described in the legend of Fig. 1. (A–C) Reported are the mean ± SE of at least three different experiments. (D) Histogram overlay of one representative donor evaluated after 4-h coculture. *p < 0.05, **p < 0.01 in the Tukey HSD test.
This was accompanied by an enhanced degranulation and also effective killing of the target cells as measured in a classical [51Cr] release assay (Fig. 6B). Effector cells also acquired the ability to kill tumor cells, as representatively shown for the melanoma cell line Mel1379 (Fig. 6C).

**Different requirements for cytokine secretion and development of cytotoxicity**

To dissect the mechanisms of the enhanced innate activation, DC were incubated with PBL in the presence of the isotype control or blocking Abs directed against IL-12p70 prior to their functional
evaluation. Upon 16-h incubation with alt-2 DC in the presence of the anti–IL-12p70 Ab, NK and \( \gamma \delta \) T cells almost completely lost their ability to secrete IFN-\( \gamma \) (Fig. 7A), whereas no statistically significant alteration in their degranulation in response to Daudi cells was found (Fig. 7B). In addition to the loss of IFN-\( \gamma \) secretion, a slight and statistically not significant increase of IL-10 (\( p = 0.068 \)) and TNF-\( \alpha \) (\( p = 0.12 \)) was found in the coculture supernatants, whereas IL-1b and IL-6 secretion remained unaffected (Fig. 7C) and cytokines corresponding to other immune polarizations were still not detected (data not shown). Blockade of IL-12p70 in the long-term coculture confirmed the independence from IL-12p70 for the degranulation in response to Daudi (left) or Mel1379 cells (right). Data represent mean ± SE of four to six different donors. *\( p < 0.05 \), **\( p < 0.01 \) in the Tukey HSD test.

**FIGURE 6.** Alternative DC-promoting effects on innate cells are long lasting. Total PBL were stimulated with autologous mature DC (10:1 ratio) for 8 d in X-vivo 15 medium before functional evaluation against target cells. The stimulated PBL were incubated for 4 h with Daudi cells (A, B) or the melanoma cell line Mel1379 (C). Secretion of IFN-\( \gamma \) (A) and CD107a degranulation assays (B, C; top) were performed at a 1:1 ratio between PBL and target cells and effector populations identified upon counter staining, as described in the legend of Fig. 1. Represented are the mean ± SE among five different experiments. Daudi and Mel1379 were also labeled with [51Cr] and incubated for 4 h at different E:T ratios with PBL in triplicates for a standard chromium release assay (B, C; bottom). Represented are the mean ± SD of one experiment of four with similar results. *\( p < 0.05 \), **\( p < 0.01 \) in the Tukey HSD test.

**FIGURE 7.** IL-12p70 is required for induction of IFN-\( \gamma \) secretion. (A–C) PBL were incubated for 16–21 h with alt-2 DC in the presence of 10 \( \mu \)g/ml isotype control or anti–IL-12p70 mAb. Secretion of IFN-\( \gamma \) (A), degranulation to Daudi cells (B), and cytokine content in the supernatants (C) were evaluated, as described in legend to Figs. 3 and 5. Data represent mean ± SE of four different experiments. *\( p < 0.05 \), **\( p < 0.01 \) in paired t test. (D) PBL were incubated for 8 d with alt-1 or alt-2 DC in the presence of 10 \( \mu \)g/ml isotype control or anti–IL-12p70 mAb before the degranulation in response to Daudi (left) or Mel1379 cells (right) was evaluated. Data represent mean ± SE of one of four with similar results. *\( p < 0.05 \), **\( p < 0.01 \) in the Tukey HSD test.

Excessive innate activity is counterproductive for Ag-specific CTL expansion

To determine the consequences of the enhanced activation of innate effector cells on the adaptive immunity, DC were pulsed with synthetic peptides and used to stimulate CD8+ T cells either purified or within total PBL. To investigate a cancer-related setting, HLA-A2+ DC were pulsed with the MelanA/Mart-1 peptide and cocultured with effector cells for 10 d in the presence of IL-2 and IL-7. When the DC were used to stimulate purified CD8+ T cells, alt-1 and alt-2 DC were able to strongly expand MelanA/Mart-1–specific T cells, as evaluated by staining with specific tetramers (Fig. 8A). In contrast, in the presence of the other immune cell populations of total PBL, a reduced expansion of MelanA/Mart-1–specific CD8+ T cells by alternative DC was obtained, whereas there was an improvement in gold standard DC performance (Fig. 8A).
were pulsed with MelanA/Mart-1 peptide and incubated with purified CD8+ T cells from healthy donors. Depletion of other immune populations was performed by CD8+ T cell purification (CD8+ PBL) and irradiated MelanA/Mart-1–pulsed PBL before being evaluated in a CD107a degranulation assay. Ag-specific degranulation was detected not only in response to peptide-pulsed T2 cells (Fig. 8C, top left), but also to endogenous Ag presentation from the Mel1379 cell line (Fig. 8C, top right). The low levels of degranulation in response to T2 cells pulsed with an unrelated peptide as well as to the MelanA/Mart-1–negative melanoma cell line Na8 (Fig. 8C, bottom) respectively confirm and support the Ag specificity of the induced degranulation.

To dissect a possible negative role of NK cells on the expansion of Ag-specific T cells, which might be either due to the adaptation of CD56+ NK cell to lyse MHC class I–positive T cells and mature DC (19, 20) or due to a NKG2D ligand-dependent killing of recently activated CD8+ T cells (21, 22), the same coculture experiment was performed with PBL depleted of NK cells. Because in some donors the MelanA/Mart-1 tetramer-positive CD8+ T lymphocytes were CD56+ (data not shown), the following strategy was used: CD8α+ cells were first purified from the total PBL and the remaining negative fraction either was left untreated or underwent depletion of CD56+ cells before being added to the DC–CD8+ T cell coculture. The absence of CD56+ NK cells was not enough to restore the expansion of MelanA/Mart-1–specific T lymphocytes to the levels of the purified setting, but there was a trend, even if not reaching statistical significance toward an increased expansion (Fig. 8B).

The CD8+ T cell cultures containing expanded amounts of MelanA/Mart-1–specific T cells were restimulated with peptide-pulsed, irradiated HLA-A2* PBL for 10 d and tested in a degranulation assay. Ag-specific degranulation was detected not only in response to peptide-pulsed T2 cells (Fig. 8C, top left), but also to endogenous Ag presentation from the Mel1379 cell line (Fig. 8C, top right). The low levels of degranulation in response to T2 cells pulsed with an unrelated peptide as well as to the MelanA/Mart-1–negative melanoma cell line Na8 (Fig. 8C, bottom) respectively confirm and support the Ag specificity of the induced degranulation.

In the next step, pools of viral peptides were used to pulse mature DC to stimulate memory CD8+ T cells within total PBL. [31Cr] release (data not shown) and CD107a degranulation assays revealed a high level of variability in the Ag-specific immune response among different donors, not only in its intensity, but particularly in the behavior of the different DC, as representatively shown for two donors with opposite situations (Fig. 9). Higher Ag-specific CD8+ T cell responses were obtained in donors with a low reactivity of innate effector cells, as determined by the killing of Mel1379 as well as of Daudi cells. In such donors, alternative DC induced the highest levels of Ag-specific CD8+ T cell–mediated responses (Fig. 9, top panels). In contrast, donors with a higher responsiveness of innate effectors to Daudi cells exerted lower CD8+ T cell–mediated responses with alt-2 DC inducing the lowest levels of Ag-specific responses, whereas the gold standard induced the highest (Fig. 9, bottom panels).

Discussion

The limited clinical objective responses obtained in tumor immunotherapy in general and also in the DC-based vaccination indicate the urgent need to optimize the currently used protocols and to increase the knowledge of the induced immune responses to select for each patient the most effective vaccine schedule.

In this study, different alternative maturation mixtures were compared with the clinical gold standard for their effect on the ability of monocytes differentiated with a fast protocol toward DC to interact with effector cells of the innate and adaptive immune system. The experiments employed fast DC because in preliminary experiments comparison with standard day 5 monocyte-derived DC highlighted not only an increased cell yield, but also a more potent induction of allogeneic MLR and higher secretion of IL-12p70 (data not shown).

Concerning the phenotype of the fast DC, as determined by the expression of costimulatory molecules and by the IL-12p70/IL-10 ratio, and their ability to activate the immune system, the alt-3 DC (TNF-α + IL-1β + IFN-γ + CL097) were almost comparable to the gold standard DC (TNF-α + IL-1β + IL-6 + PGE2). In contrast, alt-2 DC (MPLA + IFN-γ) exerted a similar and, particularly
in respect to $\gamma^\delta$ T cells, even better activity than alt-1 DC, the $\alpha$-type 1–polarizing DC initially proposed by Mailliard et al. (10) (TNF-$\alpha$ + IL-1$\beta$ + IFN-$\alpha$ + IFN-$\gamma$ + polyIC). A possible explanation is that, despite secreting similar levels of IL-12 with a donor-dependent prevalence of one DC type over the other, alt-1 DC secrete throughout all donors significantly higher amounts of IL-10 that might dampen the type 1–oriented, IL-12–induced immune response.

Regarding the functional activation of the immune system, two different processes could be identified. The first one, induced to a different extent by all alternative DC, consists in the acquisition of the cytotoxic activity and secretion of proinflammatory and type 1 cytokines via a mainly IL-12–independent signaling. Indeed, only $\gamma^\delta$ T cell cytotoxicity revealed an IL-12 dependency and only in response to difficult targets like melanoma, but not Daudi cells. In the second process, IFN-$\gamma$ secretion is induced by a highly IL-12–dependent mechanism that is performed only by alt-1 and alt-2 DC.

Despite the highly variable frequencies in the different donors, it is noteworthy that both NK and $\gamma^\delta$ T cells were activated by the alternative DC, thus leading to the activation of multiple effector mechanisms that can be useful in the coordinated action against the tumor.

The important role of NK cells for the treatment of cancer has been initially highlighted by their involvement in the graft-versus-leukemia effects obtained in acute myeloid leukemia patients undergoing haploidentical stem cell transplantation (23). More recently, solid tumors like melanoma and renal cell carcinoma also have been evaluated in vitro for their susceptibility to matched and mismatched NK cells, confirming an increased cytotoxicity upon usage of NK cells with at least one killer cell Ig-like receptor (KIR) mismatch (24). Because in our setting a KIR typing of the PBL was not performed, the intensity of the obtained tumor killing might be biased by a mismatched situation that would not exist in vaccinated patients, in which DC-activated autologous NK would interact with the autologous tumor. In our study, alt-1 and alt-2 DC induced a potent activation of CD56$^{bb}$ and CD56$^{dim}$ NK subsets regarding their cytokine production and cytotoxic activity, a finding that is in line with other reports describing IFN-$\gamma$ secretion of the CD56$^{dim}$ subset (25, 26), as well as cytotoxic activity of the CD56$^{bb}$ population (20). In contrast to Jiang et al. (20) demonstrating a granzyme K–mediated killing in the absence of granzyme B in the CD56$^{bb}$ population, a significant induction of granzyme B upon alt-1 and alt-2 DC stimulation was detected. Due to the limited amount of CD56$^{bb}$ cells in the peripheral blood, this subset could not be purified to validate target killing by standard $^{51}$Cr release assay and to assess the involved effector molecule(s). In line with the increasing reports of memory-like NK cells (27), the enhanced activity of NK was preserved 5–10 d after the stimulation with DC. Whether this correlates with the induction of memory-like NK cells, or represents a result of an expanded memory population in some of our healthy donors is currently under investigation.

In contrast to the more intraepithelial V61$^+$ cells, the V82$^+$ cells are normally regarded as the blood-born subset of $\gamma^\delta$ T cells. Despite that, they have been found within the infiltrating lymphocytes of different tumor histotype (28–30), and their ability to infiltrate human skin and perform endothelial transmigration has been documented (31, 32). For these reasons, their role in the antitumor therapy is currently being investigated in phase I/II clinical trials of adoptive transfer therapy (33, 34). In our setting, alt-2 DC were more efficiently activating the V82$^+$ $\gamma^\delta$ T cells, particularly regarding proliferation and degranulation to the melanoma cell line. Although the presentation of the lipid A moiety of LPS in association with CD11b or CD1c to $\gamma^\delta$ T cells has been proposed (35), a direct stimulation of $\gamma^\delta$ T cells by MPLA could be excluded because classical monocyte-derived DC or Langerhans-like DC stimulated with the alt-2 mixture was not able to induce IFN-$\gamma$ secretion in $\gamma^\delta$ T cells despite their higher expression of CD11b and/or CD1c in comparison with fast DC (data not shown). The results from the long-term blockade of IL-12 highlighted a statistically significant inhibition of the degranulation in response to Mel1379, but only upon stimulation with alt-2 DC. Whereas the response to alt-1 DC by $\gamma^\delta$ T cells was in general low, and thus the effect of inhibition less evident, the reduction of alt-2 DC-induced killing to levels similar to the basal alt-1 DC suggested a synergy between IL-12 and another to date undefined factor/molecule for the enhanced stimulation of $\gamma^\delta$ T cells by alt-2 DC. Among the molecules already involved in the interaction of $\gamma^\delta$ T cells with phagocytogen-pulsed tumor cells (36–38), CD86 is the only marker significantly stronger expressed in alt-2 DC compared with the other DC populations investigated, and might thus be a possible candidate for the synergic partner. Whereas the constitutive and short-time incubation with DC–induced CD56 expression was highly donor variable and not correlating with function, a consistent CD56 upregulation was found in all donors upon long-term incubation with alternative DC and correlated with enhanced proliferation/degranulation, as previously reported for in vitro expanded $\gamma^\delta$ T cells from neoplastic and infectious setting (39, 40). Thus, CD56 might represent a marker for immunomonitoring $\gamma^\delta$ T cell vaccine-induced immune responses.

Evaluation of the consequences of the potent innate activation on the induction of Ag-specific immune response highlights a complex immune context and underscores the importance of evaluating the
potency of new vaccine formulations within total blood lymphocytes and not with purified cell populations. Whereas alt-2 DC significantly improved the expansion of MelanA/Mart-1–specific T cells within purified CD8+ lymphocytes over gold standard DC, this advantage was almost completely lost within total PBL. Usage of viral Ags to evaluate the functionality of the expanded CD8+ T cells within total PBL highlighted a broad variability among different donors regarding the potency of the memory responses, ranging from <1% to >30% of responding cells, and the relative efficiency of the various DC formulations. Donors with a reduced activation of innate cells exerted higher CD8+ T cell–mediated immune responses, which were stronger upon alternative DC stimulation. In contrast, in donors with higher innate activity, a much lower frequency of degranulating CD8+ T cells existed, with the best Ag-specific responses detected with gold standard or alt-3 DC. However, the killing induced by alt-2 DC either via CD8+ T cells or innate cells was consistently higher when compared with the other DC preparations, as highlighted by the [51Cr] release assay. The mechanisms responsible for this dichotomy between an Ag-specific and an innate mediated tumor killing might be due to the following: 1) Competition of effector cells for target during the assay. Despite the 1:1 ratio used in the degranulation assay, it is possible that in donors with higher levels of HLA and/or KIR mismatching with the used target cells, the enhanced innate killing might lead to the lack of targets for the adaptive response (2). The different outcome might be also mediated by different processes during the DC priming. The only slight recovery of the expansion upon NK depletion from the cultures confirms the existence of a negative role of NK cells on CD8+ T cell priming, although this appears to be of marginal importance. With regard to the γδ T cells as another candidate, there exist discrepant results regarding the induction of Ag-specific CD8+ T cell responses. Whereas Taka-hara et al. (41) demonstrated a positive effect, Traxlmary et al. (42) described an expansion of suppressive γδ T cells reducing the expansion of CD4+ and CD8+ T cells upon stimulation with DC matured with LPS and IFN-γ. The possible development of a γδ T cell–based negative feedback loop upon PBL stimulation with alt-2 DC is currently under investigation. However, it has to be underlined that MPLA shares much of the stimulatory activity of LPS, but does not induce the toxic cytokine storm (43), suggesting that the alt-2 DC could lack this negative effect.

Overall, monocytes differentiated with the fast protocol and matured with a combination of MPLA and IFN-γ provide the strongest activation of the immune system, evaluated as secretion of type I cytokines, proliferation, and release of cytotoxic granules upon interaction with melanoma cell lines. Due to the dichotomy between the induction of a CD8+ T cell–mediated or innate-mediated killing of tumor cells, the identification of markers able to predict the response of the innate and adaptive immune system of patients is required to focus the vaccine DC formulation toward the best responses. This might be mediated, for example, by choosing between the addition of antigenic peptides versus ligands for a sustained activation of innate effector cells like γδ T or also invariant NKT–T cells.

Disclosures

The authors have no financial conflicts of interest.

References


35. Cui, Y., L. Kang, L. Cui, and W. He. 2009. Human gammadelta T cell recognition of lipid A is predominately presented by CD1b or CD1c on dendritic cells. *Biol. Direct* 4: 47.


Online Material

Figure S1. Alternative DC induce activation markers on innate lymphocytes

PBL were incubated for 16 h with mature DC in X-vivo15 and thoroughly washed before the expression levels of the activation markers CD25 and CD69 were evaluated by flow cytometry. The different effector populations were identified upon counter staining with mAb directed against CD3, CD56, CD16 and Vδ2 as described in legend to Figure 1. The mean ± SE of four different donors are shown for CD25 (A) and CD69 (B). C) Representative dot plots of “gold-standard” and “alt–2” DC stimulated CD56br (top) and CD16+56dim NK (center) as well as γδ T cell (bottom) from one representative donor are shown.
Figure S1