

Vaccination Of Pediatric Solid Tumor Patients with Tumor Lysate-pulsed Dendritic Cells Can Expand Specific T Cells and Mediate Tumor Regression¹

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ABSTRACT

Dendritic cells (DCs) have been shown to be a promising adjuvant for inducing immunity to cancer. We evaluated tumor lysate-pulsed DC in a Phase I trial of pediatric patients with solid tumors. Children with relapsed solid malignancies who had failed standard therapies were eligible. The vaccine used immature DC (CD14-, CD80+, CD86+, CD83-, and HLA-DR+) generated from peripheral blood monocytes in the presence of granulocyte/monocyte colony-stimulating factor and interleukin-4. These DC were then pulsed separately with tumor cell lysates and the immunogenic protein keyhole limpet hemocyanin (KLH) for 24 h and then combined. A total of 1×10^6 to 1×10^7 DC are administered intradermally every 2 weeks for a total of three vaccinations. Fifteen patients (ages 3–17 years) were enrolled with 10 patients completing all vaccinations. Leukapheresis yields averaged 2.8×10^8 peripheral blood mononuclear cells (PBMC)/kg, and DC yields averaged 10.9% of starting PBMC. Patients with neuroblastoma, sarcoma, and renal malignancies were treated without obvious toxicity. Delayed-type hypersensitivity (DTH) response was detected in 7 of 10 patients for KLH and 3 of 6 patients for tumor lysates. Priming of T cells to KLH was seen in 6 of 10 patients and to tumor in 3 of 7 patients as demonstrated by specific IFN- γ -secreting T cells in unstimulated PBMCs. Significant regression of multiple metastatic sites was seen in 1 patient. Five patients showed stable disease, including 3 who had minimal disease at time of vaccine therapy and remain free of tumor with 16–30 months follow-up. Our results demonstrate that it is feasible to generate large numbers of functional DC from pediatric patients even in those highly pretreated and with a large tumor burden. The DC can be administered in an outpatient setting without any observable toxicity. Most importantly, we have demonstrated the ability of the tumor lysate/KLH-pulsed DC to generate specific T-cell responses and to elicit regression of metastatic disease.

INTRODUCTION

Although there have been a number of major advances made in the treatment of childhood malignancies, cancer remains the second most common cause of death for children >1 year of age in the United States (1). In addition, many of the successful cancer therapies are associated with significant toxicity leading to long-term morbidity and an increasing second malignancy rate (2, 3). New therapies that offer less toxicity and greater potential for cure are clearly needed. With the rapid progress in our understanding of the immune system, immunotherapy is moving closer to becoming an additional modality of anticancer therapy. By using a patient's own immune system to generate antitumor responses, immunotherapy should have fewer side

effects and, more importantly, the opportunity to generate long-term immunity.

A number of significant advancements in our understanding of the immune response to cancer have brought us closer to realizing the potential of cancer immunotherapy: (a) it has been recognized that tumors express unique gene products, such as melanoma antigen E-1 (4), carcinoembryonic antigen (5), and HER-2/*neu* (6), which can be presented to in the context of the MHC complex leading to the generation of specific effector T cells (7); and (b) there is a growing body of information from both preclinical and clinical studies to indicate that DCs³ are the cells that initiate and direct the immune response leading to tumor regression (8–10).

Hsu *et al.* (11) reported that DC pulsed with a tumor antigen could elicit specific tumor-reactive T cells and have clinical efficacy in patients with lymphoma. A number of other Phase I and early Phase II clinical trials support the idea that DCs presenting TAAs can lead to partial or complete regression of tumors (12–15).⁴ To date, all of the initial clinical trials of DC-based vaccines have been completed in adults. We have completed the first Phase I trial of tumor lysate-pulsed DCs in the therapy of several different pediatric solid tumors; the early clinical results of the trial were reported previously (16). Here we report details of the clinical results for all patients enrolled, as well as describe the immune analysis of the vaccinated patients.

MATERIALS AND METHODS

Eligibility Criteria. Patients with relapsed solid tumors who had failed standard therapies were eligible for the study. Patients were required to have a source of tumor, a lymphocyte count >1000, and a good performance status. Anergy was assessed by measuring DTH to the common recall antigens candida albicans and tetanus; however, patients were not excluded if found to be anergic. Patients who had undergone an allogeneic bone marrow transplant previously were excluded.

Clinical Protocol

Tumor Cell Culture. Pediatric solid tumor samples were received at the Mott Children's Hospital, Ann Arbor, MI. Fresh sterile tumor was transported on ice to the laboratory where a combination of mechanical and chemical dissociation was used to create a single cell suspension. Chemical digestion was completed by incubation in 50-ml RPMI (BioWhittaker, Walkersville, MD), 0.00044% DNase I (Sigma Chemical Co., St. Louis MO), 150 units/ml collagenase (Sigma Chemical Co.), and 750 units/ml hyaluronidase (Sigma Chemical Co.) with constant stirring for 3–12 h. The resulting cell suspension was passed through a 70- μ m cell strainer. The flow-through was pelleted, resuspended in DMEM (Life Technologies, Inc., Grand Island, NY)/10% heat-inactivated fetal bovine serum (BioWhittaker)/1 \times Transferrin-Insulin-Selenium A (Life Technologies, Inc.), and cultured in a tissue culture flask at

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³ The abbreviations used are: DC, dendritic cell; KLH, keyhole limpet hemocyanin; IL, interleukin; PBMC, peripheral blood mononuclear cell; DTH, delayed-type hypersensitivity; FACS, fluorescence-activated cell sorter; TAA, tumor-associated antigen; PBSC, peripheral blood stem cell; ELISPOT, enzyme-linked immunospot assay; SI, stimulation index; i.d., intradermal; DPBS, Dulbecco's phosphate buffered saline.

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37°C, 5% CO₂. Trypsin-EDTA (Life Technologies, Inc.) was used to passage tumor cell lines. For long-term storage, tumor cells were frozen in 90% human AB serum (BioWhittaker) and 10% DMSO.

Preparation of Tumor Lysates. Tumor cells (fresh or short-term cultured cell lines) were suspended in PBS. The cell suspension was frozen in liquid nitrogen for 1.5 min, then thawed in a 37°C water bath for 4 min. The freeze-thaw cycle was repeated three times in rapid succession; cells were irradiated at 10,000 cGy and stored in liquid nitrogen for later use.

Leukapheresis Protocol. Using the COBE Spectra apheresis machine, we selected either a WBC or an Auto PBSC tubing set to collect the cells. Children <20 kg required a blood prime to maintain hemodynamic stability; for these patients, we used a WBC set to perform a "manual" cell collection. Children >20 kg can tolerate the procedural fluid shifts, and, therefore, "automated" cell collection is performed. Flow rates are determined by the child's size as the machine has an extensive algorithm to determine anticoagulant tolerance. We processed two to three times the patient's blood volume, which averaged 3–4 h/procedure.

Venous access was accomplished by either two large peripheral arm veins, if the patient was cooperative, or, as in most cases, by a rigid dialysis catheter placed in the femoral vein and then removed postleukapheresis. Product volumes varied depending on the type of collection performed. WBC/manual collection yielded a product of ~100–250 ml, whereas auto PBSC was more concentrated yielding 40–100 ml. We routinely measured the patient's ionized calcium level and titrated a calcium gluconate drip to maintain the ionized calcium at 1–1.3 mM.

DC Generation and Vaccine Preparation. The generation of DC and preparation of the vaccine was performed according to IND #BB6958 filed with and approved by the Food and Drug Administration. Cell cultures and antigen pulsing were performed in the Human Applications Laboratory of the University of Michigan's General Clinical Research Center, which is a facility that operates under good manufacturing procedures. The PBMCs were recovered from leukapheresis product by density gradient centrifugation over Accu-Prep Lymphocytes (Accurate Chemical & Scientific Corp., Westbury, NY). The PBMCs were resuspended in X-VIVO 15 medium (BioWhittaker) at 1×10^7 cells/ml, and 30 ml of cell suspension were added to each 225-cm² tissue culture flask (Costar). The flasks were incubated in 5% CO₂ at 37°C, and after 2 h, the nonadherent cells were gently removed. The adherent cells were cultured in X-VIVO 15 medium containing recombinant human granulocyte/monocyte colony-stimulating factor (100 µg/ml; Schering-Plough, Kenilworth, NJ) and recombinant human IL-4 (50 µg/ml; Schering-Plough) for 6 days. After 6 days, the DCs were harvested by adding 10 ml of 3 mM EDTA-PBS. A total of 1×10^7 DC was transferred to 75-cm² flasks (Costar) and either pulsed at a 1:1 ratio with autologous tumor lysates or 300 µl of KLH stock solution (50 µg/ml; Calbiochem, San Diego, CA).

Pulsed DCs were incubated for 18 h, harvested by incubation in PBS, washed twice with PBS, and then harvested and combined for vaccine administration. Autologous DCs (1×10^7) in 400 µl of PBS were prepared for i.d. administration.

Study Design. The primary end points for the Phase I study were to assess feasibility and toxicity of the DC vaccination regimen. The National Cancer Institute Common Toxicity scale was used. Secondary end points were to assess immune responses induced by the vaccination procedure to the marker antigen KLH and to autologous tumor. The patients were given a total of three vaccinations i.d. near the inguinal lymph nodes. The first 3 patients received 1×10^6 cells; the dose was then escalated to 1×10^7 cells in subsequent patients. All vaccinations were administered in an outpatient clinic of the General Clinical Research Center. One month after the last vaccination, patients underwent follow-up imaging studies, repeat leukapheresis for immune monitoring, and DTH testing to KLH and autologous tumor. Standard criteria for tumor response were used. Patients with partial responses or stable disease were eligible for a second set of vaccinations if adequate tumor was available. This protocol was approved by the University of Michigan's Institutional Review Board (96-213). Informed consent was obtained from each patient's legal guardian before enrollment.

Immune Response

Skin Tests. Tumor lysates were diluted in DPBS and administered in the following doses in 0.5 ml of volume: 1×10^5 , 1×10^6 , and 1×10^7 tumor

equivalents. For KLH skin tests, 200, 20, and 2 µg of KLH were suspended in 200 µl of DPBS and administered i.d. Induration was measured 48 h later in two perpendicular diameters. Positive DTH reactions were judged as positive if the average perpendicular measurements exceeded 5 mm.

ELISPOT. ELISPOT plates (Polyfiltronics) were coated with 100 µl/well α-IFN-γ monoclonal antibody (Endogen, Woburn MA) at 4 µg/ml in sterile PBS (BioWhittaker) wrapped in Saran wrap and incubated overnight at 4°C. Plates were washed twice with 200 µl of PBS and blocked with 200 µl of X-VIVO/10% heat-inactivated human AB serum (BioWhittaker) for 1 h at room temperature. Blocking solution was removed from the plate. Unstimulated PBMC samples were plated in triplicate as follows: each well contained 1×10^6 PBMC in 200 µl of X-VIVO15/2% human AB serum with or without 8 µg of KLH (Sigma Chemical Co.). Plates were incubated for 18–24 h at 37°C, 5% CO₂. Cells were removed, and plates were washed three times with PBS and three times with PBS/1%TWEEN-20 (Sigma Chemical Co.). Biotinylated anti-IFN-γ monoclonal antibody (100 µl; Endogen) at 4 µg/ml in PBS/1%TWEEN-20/10% heat-inactivated human AB serum was added to each well. Plates were incubated 2 h at room temperature or overnight at 4°C. Plates were then washed six times (≥2 min each) with 200 µl of PBS/1%TWEEN-20. Streptavidin-horseradish peroxidase (Dako, Carpinteria, CA) was diluted 1:2000 in PBS/1%TWEEN/10% heat-inactivated human AB serum, and 100 µl were added to each well. Plates were incubated 90 min at room temperature, then washed six times (1 min each) with PBS/1%TWEEN-20 and washed twice with PBS.

3-Amino-9-ethyl-carbazole solution [100 mg of 3-amino-9-ethyl-carbazole (Pierce) in 10 ml of N,N-Dimethyl Formamide] was diluted 1:30 in 0.1 M acetate buffer. Then 30% H₂O₂ was added 1:2000 to this solution, and 200 µl were immediately added to each well of the ELISPOT plate. After development of spots, the reaction was stopped with distilled water. Plates were inverted and allowed to dry overnight protected from light. Spots were counted using the ImmunoSpot Series 1 Analyzer (Cellular Technology, Ltd., Cleveland, OH).

Proliferation Assay

PBMCs were thawed, washed, and suspended in X-VIVO 15 medium supplemented with 1% human AB serum (BioWhittaker), 2 mM glutamine, 100 units of penicillin, 10 mg/ml streptomycin, and 50 µM 2 mercaptoethanol (Sigma Chemical Co.). Viability was assessed by trypan blue exclusion, and cell concentration was adjusted to 6×10^6 /ml. Cells were added to 96-well, round-bottomed plates in 100-µl volumes and incubated in a final volume of 200 µl with either medium alone, KLH (40 µg/ml), or tumor lysate (prepared to deliver lysate at tumor cell equivalence) for a total of 6 days at 37°C, 5% CO₂. Phytohemagglutinin (Sigma Chemical Co.) was added to some of the wells as a positive control on day 3. The cultures were pulsed with 1 µCi/well of [³H]thymidine (ICN, Costa Mesa, CA) on day 5 and incubated overnight before harvest onto glass fiber filter plates (Millipore, Bedford, MA). Data were collected on a TopCount NXT scintillation counter (Meriden, CT). An SI was calculated: SI = average cpm of antigen-stimulated culture/average cpm of unstimulated culture.

FACS Staining. Cells (5×10^5) were suspended in 50 µl of diluted FITC-conjugated monoclonal antibody (CD3, CD4, CD8, CD25, CD28, CD45RA, CD45RO, CD57, and CD69; PharMingen). They were incubated for 30 min at 4°C in the dark and then washed two times with FACS buffer (DPBS/2% fetal bovine serum/0.1%NaN₃). They were resuspended in 500 µl of 1% paraformaldehyde in PBS. Data were analyzed using the Becton Dickinson FACSCalibur and CellQuest v3.2.1f1.

RESULTS

Patient Characteristics. A total of 15 patients were entered into the trial, and 10 of these completed all three vaccinations and were evaluated for toxicity, immune response, and tumor response. Five other patients had from one to three vaccinations but, because of progressive disease, were not able to be fully evaluated. All of the patients enrolled in the study were heavily pretreated for relapsed disease, and 7 of the patients had undergone some form of hematopoietic transplant (autologous PBSCT or bone marrow transplant)

Table 1 Patient characteristics and clinical results^a

No.	Age	Sex	Diagnosis	Treatments before vaccination	Relapsed tumor sites before vaccination	DC dose (No. of vaccinations)	DTH response K (KLH) L (lysate) ^b	Tumor response
1	16	F	Fibrosarcoma	Surgery Chemotherapy (CCG-7921)	Lung spine-thoracic	1 × 10 ⁷ (3)	K ∅ T +	PR
2	12.5	F	PNET	Surgery Chemotherapy PBSCT	Lung-microscopic	1 × 10 ⁷ (3)	K +++ T ++	SD
3	7	F	PNET	Radiation Surgery Chemotherapy (CCG-7942B)	Thoracic-microscopic	1 × 10 ⁷ (3)	K ∅ T ∅	SD
4	4.5	F	Neuroblastoma	Radiation Surgery PBSCT	Bone marrow-microscopic	1 × 10 ⁷ (3)	K ++ T ∅	SD
5	8	M	Neuroblastoma	Anti-G _{D2} antibody Surgery BMT ^d	Lung	1 × 10 ⁶ (3)	K ∅	PD
6	4.5	F	Neuroblastoma	Radiation Surgery BMT	Adrenal bed	1 × 10 ⁶ (3) 1 × 10 ⁷ (3)	K ++ T +	SD
7	15	M	Renal cell cancer	Radiation Surgery IL-2	Retroperitoneum-lymphatic	1 × 10 ⁷ (3)	K + T ++	PD
8	15.5	M	Osteosarcoma	Surgery Chemotherapy	Lungs	1 × 10 ⁷ (3)	K +++ T ∅	PD
9	15	M	Inflammatory myofibroblastic	Steroids Surgery	Abdomen-mesenteric lymph nodes	1 × 10 ⁷ (3)	K +++	SD
10	4	M	Hepatic sarcoma	Surgery Chemotherapy	Abdomen thoracic	1 × 10 ⁶ (3)	K + T ∅	PD
11	14	M	Desmoplastic round cell	Surgery Chemotherapy	Abdominal chest wall	1 × 10 ⁷ (2)		PD
12	13	M	Ewing's sarcoma	Surgery Chemotherapy (CCG-7951) PBSCT	Lung Chest wall	1 × 10 ⁷ (3)		PD
13	3	M	Clear cell sarcoma	Radiation Surgery Chemotherapy	Brain Chest wall	1 × 10 ⁷ (3)		PD
14	14.5	M	Ewing's sarcoma	Radiation Surgery Chemotherapy PBSCT	Chest wall Lung	1 × 10 ⁷ (2)		PD
15	5	F	Wilms'	Surgery Chemotherapy (CCG-4941) BMT Radiation	Abdomen Lung	1 × 10 ⁶ (2)		PD

^a Patients in shaded area did not complete the study protocol and, thus, were not able to be evaluated.

^b +++, a positive DTH response for KLH (K) at 2 μg or tumor lysate (T) at 10⁵ tumor cell equivalents. ++, a positive DTH response for KLH (K) at 20 μg or tumor lysate (T) at 10⁶ tumor cell equivalents. +, a positive DTH response for KLH (K) at 200 μg or tumor lysate (T) at 10⁷ tumor cell equivalents.

^c Children's Cancer Group.

^d Bone marrow transplant.

before vaccination. The characteristics of the 15 enrolled patients are summarized in Table 1. A number of different extra-cranial solid tumors were treated, including primitive neuroectodermal tumor and Ewing's sarcoma ($n = 4$), neuroblastoma ($n = 3$), other sarcomas ($n = 6$), and 1 patient with renal cell cancer and another with Wilms' tumor.

Vaccine Preparation and Characterization. Leukapheresis averaged 2.8×10^8 PBMC/kg, and DC yields averaged 10.9% of starting PBMC. Thus, it was feasible to administer three DC vaccinations at 1×10^7 cells in all children. The DCs generated by this technique demonstrated characteristic morphology by light microscopy, were functional in all patients tested in an allogeneic-mixed lymphocyte reaction (data not shown), and demonstrated an immature DC phenotype by FACS analysis (CD14⁻, CD80⁺, CD86⁺, CD83⁻, and HLA-DR⁺). The level of CD83 expression did increase with pulsing and replating of the DC, as shown in a representative sample in Fig. 1, but remained relatively low.

Toxicity. There were no significant toxicities associated with the DC vaccine administrations, and all patients received their vaccina-

tions in an outpatient setting. Mild local erythema was seen after vaccine administration in the majority of the patients and usually resolved within 5 min. Four patients had an increased local reaction, with induration always <10 mm with each subsequent vaccination. None of the local reactions progressed to ulceration or required pain medicine.

A panel of autoimmune serologies was drawn at baseline and 1 month after the third vaccination. In 1 patient (patient 1) the anti-dsDNA titer turned positive, and in another (patient 2), the nuclear antibody titer turned positive to 1:160 after vaccination. In both patients, the abnormal titers later returned to normal. None of the patients in the study demonstrated any clinical signs of autoimmune disease.

Tumor Response. The primary end point of this Phase I trial was toxicity; however, patients were evaluated for clinical responses as well. The clinical results are summarized in Table 1. One patient with a fibrosarcoma with numerous metastatic nodules to the lungs and a thoracic spine mass had a significant partial response. Many of the pulmonary metastases, including one that measured 2 cm, regressed

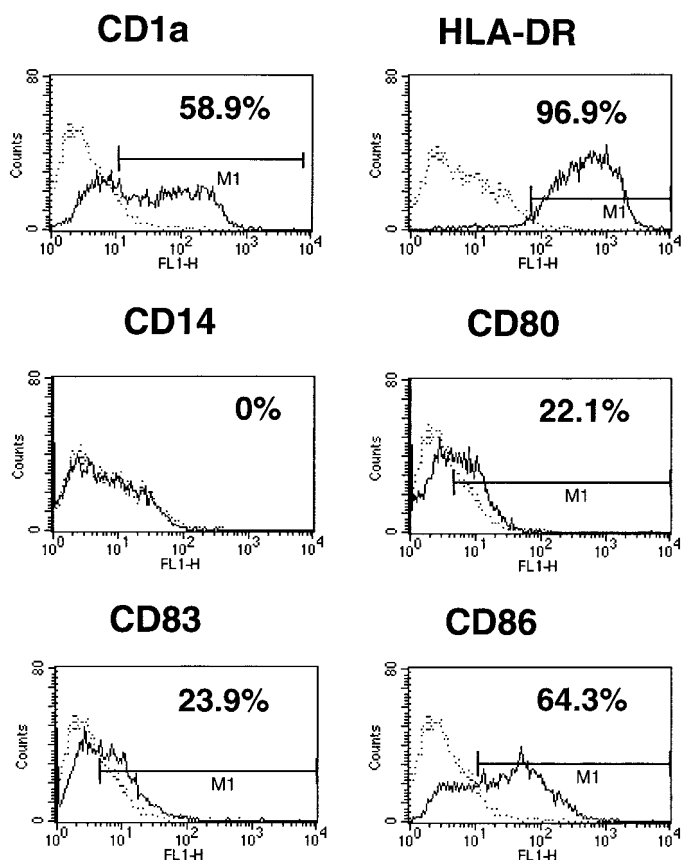


Fig. 1. FACS analysis of tumor lysate-pulsed DC (day 7). The DCs are positive for HLA-DR, CD86, CD1a, and CD80, with a low level of CD83 expression. In the histograms, the darker — represents staining with the appropriate mAb, and the lighter represents the isotype control-matched mAb (for background staining).

completely. Five patients had stable disease, including 3 who had minimal disease at the time of vaccine therapy, and have remained free of tumor with 16–30 months follow-up.

DTH Reactivity. DTH reactivity was assessed for KLH and autologous tumor (when sufficient tumor was available) in patients 1 month after the third vaccination. The DTH responses are summarized in Table 1. A positive DTH response was seen in 7 of 10 patients for KLH and 3 of 6 for autologous tumor lysates. None of the patients had prevaccine KLH DTH testing because of the potential of sensitizing to KLH leading to a false positive result on postvaccine DTH testing. A correlation between tumor DTH reactivity and clinical response could not be determined in this study.

Immune Response to KLH. Immune response to KLH was evaluated by the *in vitro* analysis of reactive cells from unstimulated PBMCs collected prevaccine and 1 month after the third vaccination in both a proliferation assay (Fig. 2) and in an ELISPOT assay (Fig. 3, *a* and *b*). In the proliferation assay, the stimulation indices of 9 subjects before vaccine were compared with stimulation indices after vaccine. On average, the SI after vaccine was 2.3 times that before vaccine.

In the ELISPOT assay, fresh unstimulated PBMCs (containing CD4⁺ and CD8⁺ cells) were evaluated for IFN- γ secretion in response to antigen stimulation. ELISPOT measurements of IFN- γ were collected in triplicate for 9 subjects, both before vaccine and after vaccine. After measurements were adjusted for background levels, 6 of 10 patients had a 2-fold (on average, 270 more IFN- γ spots) increase in the number of IFN- γ spots postvaccine compared with prevaccine (Fig. 3, *a* and *b*).

Immune Response to Tumor Lysate. Responses to tumor lysate were also evaluated in fresh unstimulated PBMCs in an ELISPOT assay for 6 patients that had adequate clinical material (Fig. 4). After vaccination, 3 of 6 patients demonstrated a >10-fold increase in the number of IFN- γ spots in response to tumor antigen. These 3 patients included patient 1, who had significant tumor regression, and patients 2 and 3, who had microscopic disease and were alive without evidence of disease at writing. Once again, the mean of each subject's response before vaccine was compared with each subject's response after vaccine via a paired *t* test. The response after vaccine demonstrated, on average, 68 more IFN- γ spots than before vaccine.

In patient 3, who had neuroblastoma, we evaluated the specificity of the antigen response in an ELISPOT assay. As shown in Fig. 5, PBMCs from the patient postvaccine responded to autologous tumor, as well as an HLA-matched neuroblastoma tumor from another patient, but not to a different histological (Wilms') tumor.

DISCUSSION

There have been a number of early clinical trials evaluating DC-based vaccines in the therapy of cancer in adult patients with melanoma, renal cell cancer, and prostate cancer (12–15). We have now shown in pediatric malignancies that it is not only feasible to generate DC in children, including those as small as 13 kg, but that DC-based vaccines can be administered in an outpatient setting without significant toxicity. Of importance, tumor lysate-pulsed DC were able to generate specific T-cell reactivity and mediate regression of established metastatic tumors in heavily pretreated patients.

In most of the DC-based immunotherapy trials to date, the DCs were generated from adherent PBMCs (CD14⁺ monocytes) cultured with granulocyte/monocyte colony-stimulating factor and IL-4, which predominantly expressed an immature phenotype. The phenotype of the DCs generated in our study was also found to be consistent with that of immature DCs (*i.e.*, no CD83), but after replating and pulsing with tumor lysates and KLH, the level of expression of CD83 tended to increase slightly. DC maturation has been shown to be accompanied by increased potency in stimulating T cells (perhaps mediated by tumor necrosis factor- α or cross-linking of CD40 by CD40 ligand) but a decreased ability to acquire and process antigen (17). We did not actively attempt to mature the DCs in our trial; however, tumor lysate, KLH, or perhaps the production of inflammatory cytokines because of replating may have led to the relative maturation observed in our cultures (18, 19). It is also possible that additional maturation of the

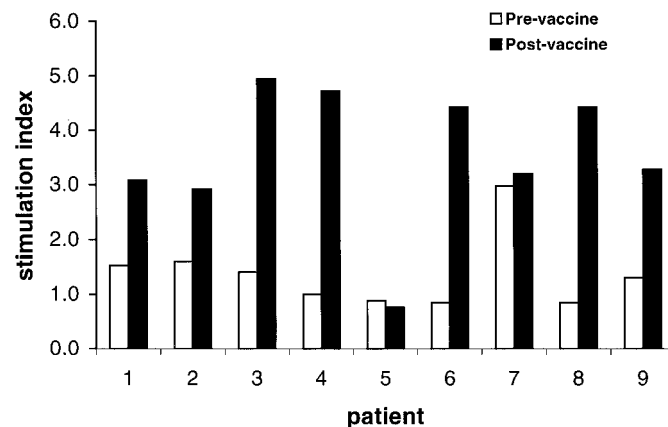


Fig. 2. KLH-specific proliferation in unstimulated PBMCs at baseline and 4 weeks after the third vaccination. For each measurement shown, 5×10^5 PBMCs were cultured with $40 \mu\text{g/ml}$ KLH for 5 days, and then proliferation was measured by the incorporation of [^3H]thymidine. Results are presented as SI.

Fig. 3. *a*, KLH-reactive T cells quantified by an ELISPOT assay. Unstimulated PBMCs (1×10^6) are cultured with or without $8 \mu\text{g}$ of KLH. Data are shown as the number of spots or reactive T cells per 1×10^6 PBMC at baseline and 4 weeks after the third vaccination. *b*, color photomicrograph of representative wells of an ELISPOT plate. Each red spot represents IFN- γ secretion by individual KLH-reactive T cells at baseline and 4 weeks after the third vaccination.

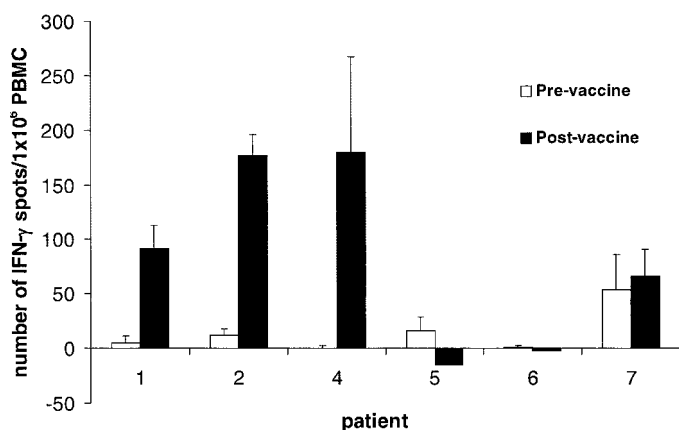
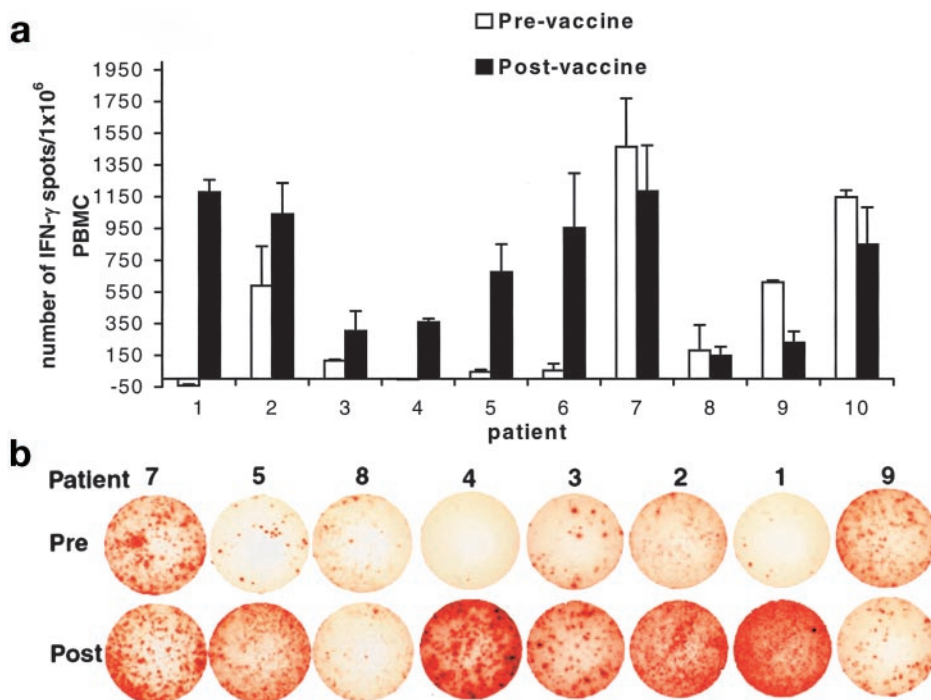


Fig. 4. Tumor lysate-reactive T cells were quantified using an ELISPOT assay. Unstimulated PBMCs (1×10^6) were cultured with or without autologous tumor lysate. Data are shown as the number of spots or reactive T cells per 1×10^6 PBMC at baseline and 4 weeks after the third vaccination.

injected DCs may occur *in vivo* after vaccine administration (20). The average DC yield of 10.9% of the starting PBMC was adequate for at least three vaccinations of 1×10^7 cells in each child. Although CD34⁺ stem cells can also be used as a source of DC, the phenotype and functional characteristics of these DCs are more variable and less studied (21, 22). The optimal source and degree of maturation of the DCs used in immunotherapy will continue to be an important area of investigation.

We initially included KLH in our vaccine strategy as a tracer antigen to evaluate vaccine efficacy as originally described by Hsu *et al.* (11). However, the role and importance of KLH to enhance the immunogenicity of vaccines have since become elucidated (23). Recently, we have shown that KLH can both increase the degree of IFN- γ secretion by tumor-specific T cells and augment the efficacy of tumor lysate or peptide-pulsed DC immunization in mediating tumor rejection in mice (24). The effect was found to be CD4⁺ T-cell dependent and could be enhanced by IL-2. Thus, the use of KLH may

be beneficial in skewing the balance of the T-cell response toward a type 1 helper response.

We have elected to use tumor lysates as the source of antigen for this study for a number of reasons, which we *et al.* (25, 26) have discussed previously. Secondly, there are only a few described TAAs, and most of these have been identified in adult malignancies, particularly, melanoma. For most pediatric malignancies, there is a paucity of well-defined TAAs, and even less clear is whether there exists actual tumor-rejection antigens. In addition, lysate as a source of antigen should lessen the potential for tumor escape because of the generation of a larger repertoire of tumor-rejection antigens (27). One potential disadvantage of using tumor lysates as a source of TAA is the need for an adequate source of autologous tumor, and in fact, this did limit our ability to treat three of the patients in this study. However, we were able to overcome insufficient amounts of tumor in some patients by the successful generation of short-term tumor cul-

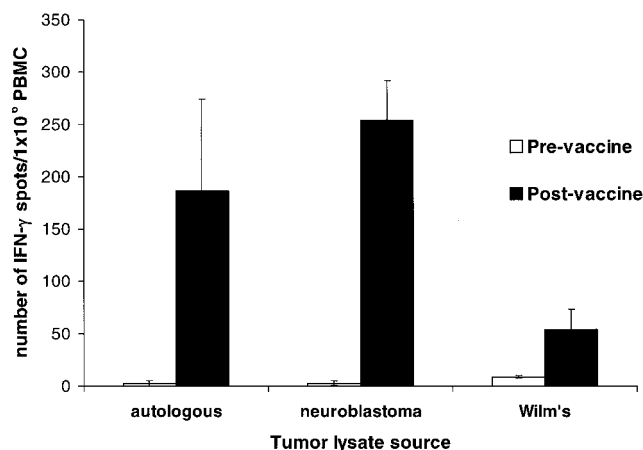


Fig. 5. Tumor lysate-reactive T cells were quantified using an ELISPOT assay. Unstimulated PBMCs (1×10^6) were cultured with or without autologous tumor lysate. Autologous tumor lysate is compared with allogenic tumor lysate from the same or different tumor type. Data are shown as the number of spots or reactive T cells per 1×10^6 PBMC at baseline and 4 weeks after the third vaccination.

tures. It might also be possible in future studies to use allogeneic tumor lines as a source of TAA (28), dependent on the discovery that shared, MHC-restricted antigens exist among pediatric tumors. Indeed, T cells from 1 patient with neuroblastoma responded postvaccine to stimulation with an allogeneic neuroblastoma tumor cell line, which may indicate shared tumor antigen(s).

One potential disadvantage of the use of tumor lysates would be the inclusion of other "self antigens" that could lead to the generation of autoimmune sequelae. Although 2 of the patients in this study had transient conversion of autoimmune serologies, both subsequently reverted back to normal. In addition, we observed no clinical autoimmune disease and no other systemic toxicity to the vaccines. Although our experience is consistent with that in other DC immunotherapy trials, monitoring for autoimmunity will continue to be important in future studies.

The optimal route of administration of antigen-pulsed DCs remains controversial. Intranasal, i.v., s.c., and i.d. routes of administration have been used in different clinical trials (12, 29). In theory, for optimal T-cell activation, it would be expected that intradermally administered antigen-pulsed DCs would migrate to the regional draining lymph nodes, where contact with T cells would be maximal. It has been shown that immature DCs have the ability to migrate rapidly to lymph nodes and that this route of inoculation is superior for DC migration to the lymph nodes than the s.c. or i.v. route (30). Recently, intranasal DC delivery was shown to be superior to the i.d. route in a murine model for generating T-cell responses (31). Nestle *et al.* (12) have shown that intranasal delivery of DCs was feasible in adults and could lead to measurable tumor regression in patients with advanced melanoma. Future trials are designed to directly evaluate different routes of DC vaccine administration.

A distinguishing feature of our study compared with DC-based vaccine trials in adult patients is how extensively pretreated the children were enrolled in our trial. Most of the patients had multimodality toxic and immunosuppressive cancer therapy with over half of the patients having hematopoietic transplants. Despite this pretreatment, 1 patient with bulky metastatic disease had a significant partial response, and 3 others with microscopic disease remain alive at this time without evidence of tumor.

There is great interest in developing immune assays that could correlate with or potentially predict clinical response (32, 33). One clinical monitoring tool is DTH testing to antigen to indicate cellular immunity. The majority of the patients in our study demonstrated DTH to KLH, and half demonstrated DTH to autologous tumor. Notwithstanding, it remains controversial whether or not DTH to autologous tumor can be a reliable correlate of clinical responses.

Quantification of active specific immune responses with immunological assays is critical to determining vaccine efficacy. The secretion of IFN- γ by antigen-stimulated T cells was shown to correlate with tumor regressions *in vivo* (34, 35). The ELISPOT assay has been found to be highly sensitive for detecting cytokine secretion by individual T cells. Thus, we used an ELISPOT assay to quantify IFN- γ secretion in response to KLH and to tumor lysates before and after DC vaccination. Of importance, the assays were performed on PBMC that had undergone no *in vitro* stimulation. The 4 patients who had better clinical responses also had significant increases in their KLH-reactive T cells, and 3 (the 4th did not have adequate tumor for the assay) had significant responses to autologous tumor lysate as well. Although MHC-peptide tetramer analysis is another sensitive method of quantifying antigen-specific cells (36), it was not used because of the lack of defined TAA epitopes in the tumors studied. Also, the correlation of MHC-peptide tetramer-identified epitopes with tumor-rejection antigens is in question (37). Despite these dramatically improved assays, there is still a need for better assays to

quantify active specific immune responses and find correlation with clinical responses.

The results of our initial experience with tumor lysate-pulsed DC vaccination in children with solid tumors indicate that this approach is feasible, and based on our clinical and immune responses, future studies seem warranted. Because of its low toxicity, indication of immune responses, and early clinical results, the use of DC-based tumor vaccines in children should be explored in the minimal disease setting, where they are likely to have more benefit.

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