Immunogenicity of a Plasmid DNA Vaccine Encoding Chimeric Idiotype in Patients with B-Cell Lymphoma

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ABSTRACT

B-cell lymphomas express tumor-specific immunoglobulin, the variable regions of which [idiotype (Id)] can serve as a target for active immunotherapy. Promising results have been obtained in clinical studies of Id vaccination using Id proteins. However, Id protein is laborious and time-consuming to produce. DNA vaccination is an attractive alternative for delivering Id vaccines, because Id DNA can be rapidly isolated by PCR techniques. DNA coding for lymphoma Id can provide protective immunity in murine models. In the present study, we performed a Phase I/II clinical trial to study the safety and immunogenicity of naked DNA Id vaccines in 12 patients with follicular B-cell lymphoma. The DNA encoded a chimeric immunoglobulin molecule containing variable heavy and light chain immunoglobulin sequences derived from each patient’s tumor, linked to the IgG2a and κ mouse immunoglobulin (MsIg) heavy- and light-chain constant regions chains, respectively. Patients in remission after chemotherapy received three monthly i.m. injections of the DNA in three dose escalation cohorts of four patients each (200, 600, and 1800 μg). After vaccination, 7 of 12 patients mounted either humoral (n = 4) or T-cell-proliferative (n = 4) responses to the MsIg component of the vaccine. In one patient, a T-cell response specific to autologous Id was also measured. Anti-Id antibodies were not detectable in any patient. Surgery, virus, and/or T-cell anti-Id responses; yet, these were cross-reactive with Id proteins from other patient’s tumors. Subsequently, a third series of vaccinations was carried out using 500 μg of human granulocyte-macrophage colony-stimulating factor DNA mixed with 1800 μg of Id DNA. The proportion of patients responding to MsIg remained essentially unchanged (8 of 12), although humoral or T-cell responses were boosted in some cases. Throughout the study, no significant side effects or toxicities were observed. Despite the modest level of antitumor immune responses in this study, DNA vaccine technology retains potential advantages in developing anti-Id immunotherapies. Additional studies are warranted to optimize vaccine dose, routes of administration, vector designs, and prime-boost strategies. These results will help guide the design of future DNA vaccine trials.

INTRODUCTION

B-cell malignancies express a tumor-specific antigen, the immunoglobulin Id, which can serve as a target for immunotherapy (1). The Id antigenic determinants are located in the variable regions of the heavy and light chains of the tumor’s clonal immunoglobulin. These structures create targets that can be recognized by antibodies as well as by CD4+ and CD8+ T cells. Tumor-specific Id proteins can be isolated from lymphoma cells using hybridoma techniques (2). The protein can be rendered immunogenic by chemical coupling to a carrier protein such as KLH and by mixing with an immunological adjuvant or with dendritic cells. Vaccination of lymphoma patients with Id proteins has been shown to induce: (a) anti-Id immune responses that correlate with improved clinical outcomes (3, 4); (b) durable tumor regressions (5, 6); and (c) molecular complete remissions (7). However, several factors currently prohibit the effective application of Id vaccination to large numbers of lymphoma patients. The isolation of Id protein from each patient’s tumor is time consuming and expensive. Moreover, coinfected immunological adjuvants often contribute side effects at the local injection site.

DNA vaccination may represent a more efficient route to anti-Id immunotherapy. Vaccination of mice with plasmid DNA expression vectors (“naked DNA vaccination”) has been shown to induce protective immune responses against a variety of infectious diseases and tumors (8–10). Plasmid DNA constructs are technically easier and less time consuming to prepare than recombinant or hybridoma-derived proteins. This is especially important in the case of a customized vaccine approach. In addition, bacterial plasmid DNA possesses inherent immune adjuvant activity based on its content of unmethylated CpG immunostimulatory sequences (11) that interact with toll-like receptors in mammalian immune cells (12). Recent technological developments make a genetic approach to idiotypic vaccination possible (13). PCR technology now allows for the rapid cloning of the variable (idiotypic) regions from immunoglobulin genes (14, 15). Genetic vaccination with Id-encoding plasmid DNA has shown efficacy in several murine lymphoma models (16–19). Syrnegalas et al. found that vaccination of mice with plasmid DNA-encoding tumor Id developed strong humoral anti-Id immune responses and were protected against subsequent tumor challenge at a rate comparable with that after vaccination with Id-KLH protein. The protection depended on the inclusion of foreign constant region immunoglobulin sequences (human) linked to the mouse variable regions, which were felt to provide a “carrier” function analogous to that provided by the KLH in the case of protein vaccination. Anti-Id immune responses were further enhanced by coinjection of DNA encoding GM-CSF (13, 16). These findings, and the development of a bicistronic immunoglobulin expression vector (20), formed the basis for the current study of DNA Id vaccination in humans.

We sought to explore the safety and immunogenicity of chimeric Id-encoding plasmid DNA vaccines with and without coinfected GM-CSF DNA in patients with lymphoma. Patient-specific plasmids were constructed to encode a chimeric immunoglobulin molecule consisting of tumor-specific variable (Id) regions linked to xenogeneic (murine) immunoglobulin constant regions, in a strategy analogous to that shown to be effective in our preclinical studies (16, 20, 21). We found

residual disease; MRD, minimal RD; i.d., intradermal; HRP, horseradish peroxidase; HbsAg, hepatitis B surface antigen.

Received 5/9/02; accepted 8/9/02.

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1 Supported by NIH Grants HL57443 and CA33399. J. M. T. is the recipient of a Clinical Cancer Society Clinical Research Professor.

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4 The abbreviations used are: Id, idiotype; PBMC, peripheral blood mononuclear cell; MsIg, mouse immunoglobulin; CMV, cytomegalovirus; GM-CSF, granulocyte-macrophage colony-stimulating factor; KLH, keyhole limpet hemocyanin; dsDNA, double-stranded DNA; CT, computed tomography; NED, no (clinical) evidence of disease; RD, residual disease; MRD, minimal RD; i.d., intradermal; HRP, horseradish peroxidase; HbsAg, hepatitis B surface antigen.
that with the doses and routes of injection used, the Id DNA vaccines were safe and that the vector was immunogenic. The majority of patients developed humoral or T-cell immune responses to the xenogeneic (murine immunoglobulin) component of the vaccine, and some patients made responses to their autologous tumor Id.

**MATERIALS AND METHODS**

**Patients.** Eligible patients were adults with untreated stage III or IV follicular B-cell lymphoma (follicle center cell grades I and II by Revised European and American Lymphoma classification). All of the patients had a peripheral lymph node of at least 2 X 2 cm accessible to excisional biopsy for diagnostic confirmation and vaccine production. Monoclonal surface immunoglobulin expression was verified using flow cytometry. Patients received initial chemotherapy with six to eight cycles of cyclophosphamide, vincristine, and prednisone (CVP). Three patients (patients 7, 8, and 13) also received four cycles of cyclophosphamide, hydroxydaunomycin, vincristine, and prednisone for failure to achieve a MRD state after CVP. Clinical responses were classified according to the standardized response criteria of Cheson et al. (22). Vaccinations were initiated a minimum of 3 months after completion of chemotherapy. Prevaccine patient evaluations included physical examination, complete blood counts, lymphocyte subset analysis, serum chemistries, rheumatoid factor, anti-dsDNA antibodies, CT scans of the chest, abdomen, and pelvis, and bilateral iliac crest bone marrow biopsies. On the day of each vaccination, and at 1 and 3 months after each series of vaccinations, laboratory studies included complete blood counts, serum chemistries, rheumatoid factor, anti-dsDNA antibodies, and humoral and cellular immune responses to MsIg and tumor Id. Three months after each vaccination series, CT scans and bone marrow biopsies were repeated; and subsequent follow-up examinations, performed every 3 months, included physical examination, complete blood counts, and serum chemistries. Repeat CT scans were performed every 6 months for the first 2 years and annually thereafter, or as clinically indicated. The prevaccine tumor status of patients was classified as NED, MRD, or RD, corresponding to the attainment and maintenance of a complete response, complete response unconfirmed, or partial responses, respectively, as specified in the Cheson criteria. The study was approved by the Institutional Review Board and Biosafety Committee of Stanford University Medical Center, and all of the patients supplied written informed consent. Patients were required to use contraception for the duration of the study.

**Production of Patient-specific Plasmid DNA Vaccines.** Tumor specimens were obtained before the initiation of chemotherapy. Total RNA was extracted from viable tumor cells obtained by Ficoll-Hypaque (Amersham Pharmacia, Uppsala, Sweden) sedimentation using RNAzol B (Tel-Test, Friendswood, TX) and was used to generate cDNA with oligo(dT) primers. Heavy- and light-chain variable regions were then PCR-amplified using family-specific leader and constant region primers as described previously (14, 15), but incorporating Sfi I restriction sites (20). The amplified, Sfi I-digested fragments of the heavy and light chains were then ligated into plasmid VCL-1632 to yield plasmids VCL-1642.XXX (Fig. 1A). Plasmid VCL-1632 is a pUC18-derived kanamycin-selectable plasmid containing the CMV promoter followed by the murine κ constant region sequence, a translational enhancer, the murine IgG2a heavy-chain sequence, and a translation terminator. The completed plasmids, thus, expressed a bicistronic RNA encoding a chimeric human-murine immunoglobulin containing tumor-specific variable regions linked to murine constant regions. Proper insertion and orientation of the immunoglobulin domains was verified in individual clones by restriction digest mapping followed by DNA sequence analysis. To confirm functional expression of the encoded immunoglobulin, purified plasmids were used to transfect VM92 (murine melanoma) cells, and the supernatants were analyzed by ELISA and Western blot to detect full-length, functional immunoreactive chimeric immunoglobulin (data not shown). The best-producing clones were then chosen for vaccine production. Plasmid VCL-1723 encoding human GM-CSF (Fig. 1B) has been described previously (23). The biological activity of plasmid VCL-1723 was confirmed by the ability of supernatants from VCL-1723-transfected VM92 cells to promote the growth of GM-CSF-dependent TF-1 cells (24). Large-scale production of clinical-grade plasmid DNAs, along with purification and quality assurance analyses, were performed as previously described (25, 26). Vaccines were formulated to contain 200, 600, or 1800 μg of Id DNA or 500 μg of GM-CSF DNA in 1.0 ml of sterile PBS, and were stored frozen until use.

**Tumor Id Protein Production.** Native tumor Id proteins were isolated for each patient using the rescue hybridoma method (3, 4). These proteins were used for in vitro assessment of anti-Id immune responses. Id proteins were purified by affinity chromatography as described previously (3).

**Vaccine Treatments.** Patients received three series of vaccinations over the course of the study as summarized in Fig. 2. Series 1 vaccinations represented a dose-escalation phase, in which three groups of four patients each received three monthly i.m. (deltoid) injections, by conventional needle and syringe, of 200, 600, or 1800 μg of the chimeric Id plasmid DNA. After the safety of the highest (1800 μg) dose level was demonstrated, these same patients were offered a repeat series of three monthly vaccinations (Series 2) at this dose level. For this series, patient 13 was substituted for patient 2, who had withdrawn from the study because of progressive disease. Series 2 injections were delivered using the Biojector needle-free jet injection device (Bioject Inc., Portland, OR). Eighty % of the dose was delivered i.m. (0.8-ml volume) and 20% was delivered to two adjacent i.d. sites in the skin of the contralateral posterior upper arm (0.1 ml each). Series 3 injections were given as in Series 2, but with the addition of 500 μg of human GM-CSF DNA admixed with the Id DNA just before injection.

**Cellular Immune Response Assessments.** T-cell proliferation assays were performed as reported previously (3, 4). Fresh PBMCs were cultured in quadruplicate in medium alone or with purified tumor Id, irrelevant Id proteins, or a murine IgG2a/κ (S1CS, Ref. 27) at 0.1, 1.0, 10, and 100 μg/ml. [3H]thymidine incorporation was measured after an overnight pulse on day 5. A
Tumor biopsy, Chemotherapy,  
Tumor Id DNA cloning and GMP production

Series #1 vaccinations  
Dose escalation Id DNA (200, 600, or 1800 µg)  
Needle & syringe, i.m.  
Monthly x 3  
17 months

Series #2 vaccinations  
1800 µg Id DNA  
Biojector; 80% i.m., 20% i.d.  
Monthly x 3  
14 months

Series #3 vaccinations  
1800 µg Id DNA + 500 µg GM-CSF DNA  
Biojector; 80% i.m., 20% i.d.  
Monthly x 3

Fig. 2. Clinical trial schema. The numbers of months indicate the time intervals between initiation of the different vaccination series.

response was interpreted as positive (+) when incorporation of more than twice background (medium alone) and prevaccine baseline was observed on two or more occasions. Responses were designated +/− when incorporation of more than twice background and prevaccine baseline was observed on only a single occasion postvaccine. Tumor-specific cytotoxicity and cytokine release by PBMCs cocultured with tumor cells were measured as described previously (6, 7).

Humoral Immune Response Assessments. Sera of all patients were analyzed for IgG anti-Id antibodies by ELISA. Tumor-derived Id proteins were of either IgM or IgG subclass depending on the type expressed by the tumor. Autologous IgM tumor Id proteins or irrelevant IgM Id proteins were captured onto microtiter plates coated with goat antihuman IgM (Biosource International, Camarillo, CA). When the tumor Id was an IgG, a recombinant Id protein was constructed containing the tumor Id linked to human IgG3 constant regions, and captured onto the plate with goat antihuman IgG3 (Biosource). The need to detect bound IgG antibodies necessitated isolation of the variable region/Id sequences from commonly used IgG constant region sequences to minimize background in the assay. The IgG3 isotype was chosen for target Id construction given its generally minor contribution to humoral responses. Prevaccine and postvaccine sera were serially diluted and allowed to bind to the target Id proteins. The reagents used to detect bound antibodies depended on the isotype of the target Id molecule. When the Id protein was an IgM, bound anti-Id antibodies of the IgG subclass were detected using polyclonal antibody (goat antihuman IgG) coupled to HRP. When the target Id protein was an IgG3, bound anti-Id antibodies were detected with a cocktail of mouse monoclonal antihuman IgG1, IgG2, and IgG4 antibodies conjugated to HRP (Southern Biotech, Birmingham, AL). In each case, HRP-conjugated antibodies to the immunoglobulin light chain (κ or λ) opposite to that of the tumor Id was also used to detect serum antibodies bound to the target Id. A response was considered positive (+) when a 4-fold increase in anti-Id titer was found compared with both the prevaccine serum and the isotype-matched irrelevant Id proteins used as specificity controls. Antibody responses to murine IgG2a/κ were measured by coating microtiter plates with mouse antibody S1C5 followed by incubation with diluted sera as above and detection using polyclonal goat antihuman IgG-HRP. A response was considered positive (+) when a 4-fold increase in anti-MsIg titer was found compared with the prevaccine serum.

Safety Assessments. Patients were observed for adverse effects for at least 1 h after each injection, and, thereafter, a diary was kept to record any local injections site reactions or other side effects. Serum was tested for rheumatoid factor and anti-dsDNA antibodies at baseline and 3 months after each vaccination series. For Series 3, evaluations also included serum creatine phosphokinase before, and 1 month after, each vaccination. Mouse IgG2a/κ in serum was measured by ELISA (sensitivity of assay <0.1 µg/ml), using S1C5 as a standard. Serum GM-CSF was measured by ELISA (R&D Systems, Minneapolis, MN). Serum antibodies against GM-CSF were measured using a sandwich ELISA technique. Recombinant human GM-CSF (Immunex, Seattle, WA) was used to coat plates, to which serially diluted patient sera were added. Bound antibodies were detected using biotinylated GM-CSF followed by streptavidin-HRP (Vector Labs, Burlingame, CA). Sensitivity of the assay was <0.05 µg/ml.

RESULTS

Dose Escalation of Lymphoma Id DNA Vaccine. This study was designed primarily to investigate the safety and immunogenicity of Id DNA vaccines in humans. The doses of DNA were chosen based on previous work in mice in which 10–100 µg were sufficient to provide protective immunity (16). Dose escalation was carried out in three groups of four patients each, with the range of doses used being 200, 600, or 1800 µg. Vaccinations given during this initial dose escalation phase of the study were designated Series 1 (Fig. 2). The prevaccine tumor status, starting vaccine dosage levels, peripheral blood CD4+ T cell counts, and immune response data for each patient are shown in Table 1. CD4+ T-cell counts were notably depressed in these patients postchemotherapy and remained so in most cases throughout the duration of the study (mean, 371 ± 119/µl; normal range, 540–1660/µl). At vaccine initiation, four patients had NED, four had MRD, and four had residual tumor in lymph nodes and/or bone marrow. The plasmid DNA was injected i.m. by needle and syringe into the deltoid region. No significant side effects or toxicities were noted other than those expected from routine i.m. injections. A minority of patients had mild local injection site tenderness lasting 1–2 days.

All 12 of the patients completed the three vaccinations and were evaluable for immune responses. Seven patients (58%) mounted immune responses to the MsIg component encoded by the DNA vaccine. There were four humoral responses, four T-cell proliferative responses, and one patient with both humoral and T-cell responses (Tables 1 and 2). Immune responses were observed in a similar proportion of patients in each dose cohort; 2/4, 3/4, and 2/4 patients in the 200, 600, and 1800 µg dose cohorts, respectively (Table 1). An example of a T-cell response against MsIg observed in patient 5 is shown in Fig. 3. In this case, the proliferation of PBMCs to MsIg was concentration dependent and was seen on multiple occasions after vaccination (data not shown). A more modest proliferative response to tumor Id was also observed at this particular time point. One other patient (patient 12), treated at the highest (1800 µg) dose level, developed a reproducible tumor Id-specific T-cell proliferative response after vaccination (Fig. 4).

Repeat Vaccinations with 1800-µg Dose Via Biojector. Given the relatively low starting doses administered during dose escalation, the low rate of anti-Id immune responses, and the demonstrated safety of the 1800 µg dose, we chose to revaccinate all of the eligible patients with this highest dose in an attempt to boost immunity. These Series 2 vaccinations began 17 months after the initiation of Series 1, after which time, adequate safety data on the 1800-µg dose cohort were available and regulatory approval had been granted. The median interval between completion of Series 1 and the start of Series 2 vaccinations was 7 months (range, 3–15 months). Patient 2 had withdrawn from the study shortly after Series 1 because of progressive disease requiring standard therapy and was replaced by patient 13. This patient and three others (patients 3, 8, and 12) had evidence of disease progression at the time of Series 2. For Series 2 vaccinations, we used a needle-free jet injection device (Biojector) to deliver 80% of the dose i.m., and 20% i.d. Prior studies had indicated that i.m. jet injection delivery of a DNA vaccine could provide superior immune...
responses over conventional i.m. injection using needle and syringe (28, 29). It was assumed that the use of the Biojector would increase the immunogenicity of any given dose of DNA; therefore, only the previously established fixed dose of 1800 μg was used in subsequent portions of the study. The incidence and severity of i.m. injection site reactions in Series 2 was indistinguishable from that seen with needle- and-syringe injections in Series 1. In addition, no appreciable local reactions were observed at the sites of i.d. inoculation. After Series 2 vaccinations, there were a total of 12 immune responses against mouse immunoglobulin detected in 9 patients (6 humoral, 6 T cell, 3 both humoral and T cell; Tables 1 and 2). Four of these nine immune responders had failed to respond after Series 1 vaccinations, whereas five of the six previously responding patients continued to display reactivity against mouse immunoglobulin. After Series 2 vaccinations, patient 12 no longer had T-cell reactivity to MsIg, yet did retain a specific T-cell proliferative response against autologous tumor Id.

Four other patients had "nonspecific" T-cell anti-Id responses and two patients had nonspecific humoral anti-Id responses in which cross-reactivity to Id proteins from other patients’ tumors was observed.

**Repeat Vaccinations Using Coinjected GM-CSF DNA.** Coinjection of plasmids encoding cytokines such as GM-CSF has been shown to augment protective immunity induced by DNA vaccines (9, 13, 16, 30). We thus chose to administer a third round of vaccinations (Series 3) to these same patients using a coinjected plasmid encoding human GM-CSF (VCL–1723, Fig. 1B) in an attempt to boost the immune response to tumor Id. Vaccines consisted of 1800 μg of the chimeric Id plasmid DNA admixed with 500 μg of GM-CSF DNA delivered via Biojector as in Series 2. Series 3 vaccinations were begun 14 months after the initiation of Series 2, after which time adequate safety data on Series 2 vaccinations was available and regulatory approval had been granted. The median interval between completion of Series 2 and the start of Series 3 vaccinations was 10 months.

### Table 1 Patient characteristics, immune responses, and long-term follow-up

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Series no.</th>
<th>Dosage in series no. 1</th>
<th>Prevaccine tumor status</th>
<th>CD4 count</th>
<th>Antibody response</th>
<th>T-cell response</th>
<th>Current status, time since (initial) chemotherapy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>200 μg</td>
<td>NED</td>
<td>280</td>
<td>+</td>
<td>+</td>
<td>NED, 52 mo</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>200 μg</td>
<td>NED</td>
<td>407</td>
<td>+</td>
<td>+</td>
<td>NED after subsequent HDCT + ASCT, 52 mo</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>200 μg</td>
<td>NED</td>
<td>457</td>
<td>+</td>
<td>+</td>
<td>NED after subsequent HDCT + ASCT, 52 mo</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>200 μg</td>
<td>MRD</td>
<td>ND</td>
<td>–</td>
<td>–</td>
<td>NED, 49 mo</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>600 μg</td>
<td>NED</td>
<td>190</td>
<td>–</td>
<td>+</td>
<td>Expired with PD, 34 mo</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>600 μg</td>
<td>NED</td>
<td>224</td>
<td>+</td>
<td>–</td>
<td>NED, 37 mo</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>600 μg</td>
<td>MRD</td>
<td>226</td>
<td>+</td>
<td>–</td>
<td>NED, 37 mo</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>600 μg</td>
<td>PD</td>
<td>244</td>
<td>+</td>
<td>–</td>
<td>NED, 37 mo</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>1800 μg</td>
<td>RD</td>
<td>330</td>
<td>+</td>
<td>–</td>
<td>Expired with PD, 34 mo</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1800 μg</td>
<td>RD</td>
<td>441</td>
<td>+</td>
<td>+</td>
<td>Expired with PD, 34 mo</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>1800 μg</td>
<td>RD</td>
<td>451</td>
<td>+</td>
<td>+</td>
<td>Expired with PD, 34 mo</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1800 μg</td>
<td>MRD</td>
<td>285</td>
<td>+</td>
<td>+</td>
<td>Expired with PD, 34 mo</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
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<td>n/a</td>
<td>372</td>
<td>+</td>
<td>+</td>
<td>Expired with PD, 34 mo</td>
</tr>
</tbody>
</table>

* Scoring of immune responses is as follows. Humoral responses: +, ≥2 dilutions above background and baseline and MsIg- or Id-specific; +/–, ≥1 dilution but <2 dilutions above background and baseline; –, <1 dilution above background and baseline; and ns, response not specific for patient’s own idiotype. Cellular responses: +, ≥2 times cpm above background and baseline at two or more time points and MsIg- or Id-specific; +/–, ≥2 times cpm above background and baseline at one time point; –, ≥2 times cpm above background and baseline at no time point; ns, response not specific for patient’s own idiotype.

a Normal peripheral blood CD4+ T-cell count range, 540–1100/μl. MsIg, mouse IgG2a/k; NED, no clinical evidence of disease; MRD, minimal residual disease; RD, residual disease; PD, progressive disease; n/a, not applicable; SD, stable disease; HDCT + ASCT, high-dose chemotherapy and autologous stem cell transplantation; ND, not done.
concentrations. Proliferation was measured on day 5 by [3H]thymidine incorporation. Results represent means ± SD of quadruplicate values.

Fig. 3. T-cell proliferative response to MsIg and tumor Id after DNA vaccination (Patient 5, 600-μg cohort). Postvaccine PBMCs were incubated with medium alone or tumor Id protein, irrelevant Id proteins, or murine IgG2a/c (MsIg) at the indicated concentrations. Proliferation was measured on day 5 by [3H]thymidine incorporation. Results represent means ± SD of quadruplicate values.

Fig. 4. Cellular proliferative response to tumor Id after DNA vaccination (Patient 12, Series 1). Postvaccine PBMCs were incubated with medium alone, tumor Id protein, or irrelevant Id protein at 100 μg/ml. Proliferation was measured on day 5 by [3H]thymidine incorporation. Results represent means ± SD of quadruplicate values.

(range, 4–12 months). By the time Series 3 vaccinations were initiated, 5 of the 12 patients had evidence of tumor progression (Table 1). The incidence and severity of i.m. injection site reactions in Series 3 were indistinguishable from that seen in Series 2, and no systemic toxicity was noted. Notably, no obvious local inflammatory reactions were observed at the sites of i.d. inoculation. After Series 3 vaccinations, there were a total of 11 immune responses against mouse immunoglobulin detected in eight patients (7 humoral, 4 T cell, 3 both humoral and T cell; Tables 1 and 2). Seven of the nine previously responding patients continued to display humoral or T-cell reactivity toward autologous tumor cells toward cryopreserved tumor cells (6, 7). No tumor-specific lysis was exhibited in any of the four cases tested (data not shown).

In some instances, immune responses to MsIg were boosted by Series 3 injections. Fig. 5 shows the T-cell proliferative response for patient 13 at baseline and after Series 2 and Series 3 immunizations. The data indicate significant enhancement of the response after the repeat series of vaccinations. Boosting of the humoral immune response to MsIg with the sequential series of DNA vaccinations is shown in Fig. 6. After Series 1, patient 5 showed no evidence of a humoral response to MsIg. However, after Series 2, a significant response was detectable, with further boosting of the response after Series 3 injections.

During the last phase of this clinical trial (Series 3), we performed additional studies to seek evidence of evoked antitumor immunity by the DNA Id vaccine. Autologous tumor cells were cocultured with fresh PBMCs both before and 1 month after Series 3 injections, as described previously (7). Supernatants of these cocultures were assayed for released tumor necrosis factor α and GM-CSF, yet no consistent tumor-specific pattern of cytokine release was observed (data not shown). We also investigated the cytotoxic activity of pre- and postvaccine PBMCs restimulated with autologous CD40 ligand-activated tumor cells toward cryopreserved tumor cells (6, 7). No tumor-specific lysis was exhibited in any of the four cases tested (data not shown).

**Safety of DNA Vaccinations.** No acute or long-term toxicities of the DNA vaccination maneuvers used have been identified in over 4 years of follow-up in this patient cohort. Five patients (patients 8, 9, 11, 12, and 13) developed modest, transient elevations of serum rheumatoid factor between Series 2 and 3 vaccinations (range, 21–58; normal level, <20). Patient 11 had a slightly elevated level of 26 at prevaccine baseline. This level peaked at 58 just prior to Series 2, subsided just prior to Series 3, and thereafter fell to within normal range. However, no patient developed clinical rheumatological manifestations or other symptoms or signs of autoimmune disease. Cases in which serum rheumatoid factors were elevated showed no obvious correlation to those in whom nonspecific anti-Id responses were

<table>
<thead>
<tr>
<th>Table 2 Summary of immune responses in vaccination series 1–3</th>
</tr>
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<tbody>
<tr>
<td>Antibody responders</td>
</tr>
<tr>
<td>MsIg</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Series 1</td>
</tr>
<tr>
<td>Dose escalation</td>
</tr>
<tr>
<td>Series 2</td>
</tr>
<tr>
<td>1800 μg</td>
</tr>
<tr>
<td>Biojector</td>
</tr>
<tr>
<td>80% i.m., 20% i.d.</td>
</tr>
<tr>
<td>Series 3</td>
</tr>
<tr>
<td>As Series 2, plus GM-CSF</td>
</tr>
<tr>
<td>DNA (500 μg)</td>
</tr>
</tbody>
</table>

<sup>a</sup> MsIg, mouse IgG2a/c; Id, autologous tumor idiotype; ns, not specific for autologous Id.

<sup>b</sup> Specific for autologous Id.

Fig. 5. Boosting of the cellular immune response to MsIg after repeat series of DNA vaccinations. Patient 13 developed a modest PBMC proliferative response to MsIg after Series 2 vaccinations (This patient did not receive Series 1). An enhanced proliferative response after a booster series of vaccinations (Series 3) is shown.
During the initial dose escalation, this response persisted throughout Series 2, but was lost during Series 3, at which time new sites of tumor became evident. Six patients had nonspecific immune responses against tumor Id. In these cases, there was reproducible humoral or T-cell reactivity against tumor Id, but also cross-reactivity with Id proteins from other patients’ tumors. Such cross-reactivities have been observed with similar frequency in our previous trials (3, 4, 6), but have not been reported to date because their significance is unknown. It is possible that they represent antigen-specific reactivity against immunoglobulin determinants shared between different tumor Ids, although this has yet to be proven. The T-cell proliferation assay used throughout our study detects primarily CD4+ T-cell activities. It is possible that our assay technique is insufficiently sensitive to detect all immune priming against Id, particularly that of class I MHC-restricted CD8+ T cells. Although we found no tumor-specific secretion of tumor necrosis factor α or GM-CSF by patient T cells after Series 3 vaccinations, the induction of T cells secreting other cytokines cannot be ruled out. The patients treated in this study had depressed CD4+ peripheral blood T-cell counts, presumably because of their prior chemotherapy, and this may have contributed to the observed low incidence of anti-Id immune responses. However, these low T-cell counts are not appreciably different from those of patients whom we have treated in other trials with protein Id vaccines and in whom anti-Id immune responses are readily measured. No obvious relationship between prevaccine CD4 counts and immune responses was evident, except that, in the three instances in which the CD4 counts were within the normal range (patients 4 and 11), both antibody and T-cell responses against MsIg were detected.

We used the same group of patients for the three phases of this study (vaccine Series 1–3), given the effort invested in the production of their customized vaccines and our principal interest in evoking therapeutic antitumor immunity. A greater proportion of patients had immune responses to MsIg or Id after the second series of vaccinations (Table 1), and several patients demonstrated further boosting of their responses after the third vaccination series. However, given our study design and the results achieved, we were unable to determine the relative contributions of the Biojector, combined i.m./i.d. injection route, and coinjected GM-CSF plasmid to the observed responses. We cannot exclude the possibility that these results are attributable solely to the repeated i.m. injections of 1800 μg of the chimeric Id DNA alone. With regards to clinical activity, only one patient (patient 4) had an objective improvement in tumor burden during the study. However, without an unvaccinated control group, we cannot exclude that the observed outcome of these patients was influenced by the DNA vaccination maneuvers.

It is important to view our results in the context of the limited data available on DNA vaccination in humans. In early trials of DNA vaccines encoding HIV or influenza antigens, the induction of antibodies, T-cell proliferation, or CTLs was reported, although most often in only a minority of patients (31). More recently, i.m. injection of DNA encoding the malarial circumsporozoite protein has been shown to induce CD8+ CTLs in a majority of naïve, healthy subjects (32). CTL responses were detectable with doses as low as 20 or 100 μg but were more frequent at higher (500 and 2500 μg) doses. Despite the induction of robust CTL responses, humoral responses to circumsporozoite protein were not detectable (33). Particle-mediated delivery of a HBsAg DNA vaccine has now been shown to efficiently induce protective antibody titers and both CD4+ and CD8+ T-cell responses in healthy volunteers (34). Thus, the immunogenicity of DNA encoding foreign proteins from infectious pathogens has been demonstrated repeatedly.

5 J. Timmerman and R. Levy, unpublished observations.
In contrast, eliciting antitumor immunity in cancer patients using DNA vaccines has proved more difficult. Hawkins et al.\(^{(15, 35)}\) constructed plasmid DNAs encoding lymphoma Id as single-chain Fv fragments (heavy and light chain variable regions joined by a flexible linker) from 10 patients with low-grade B-cell lymphoma. However, at doses of 100–500 µg delivered i.m., they failed to find evidence of anti-Id immunity.\(^{6}\) Investigators at the National Cancer Institute Surgery Branch performed a study of DNA vaccination against the melanoma differentiation antigen gp100 (36). Twenty-three patients with metastatic melanoma were treated using doses of 100-1000 µg divided between two i.m. and i.d. sites, either with or without systemic interleukin 2. In this trial, no clear signs of anti-gp100 immunity or objective tumor regressions were noted. White and Conroy (31) performed vaccination of 17 patients with metastatic coloerectal carcinoma using a dual expression plasmid encoding the self tumor antigen carcinoembryonic antigen along with HBsAg as a control. Plasmid DNA was injected i.m. at doses of 100, 300, 1000, or 2000 µg. Although dose-dependent induction of anti-HbsAg antibodies was noted, no antibody or T-cell responses against carcinoembryonic antigen were detected. This latter result is analogous to the present study, in which immune responses against the foreign component of the vaccine were frequently induced, yet responses to the relevant tumor antigen were undetectable or weak (Figs. 3 and 4). Thus, little evidence of antitumor immunity has been demonstrated using first generation tumor antigen DNA vaccines.

The results of tumor antigen DNA vaccine approaches might be improved by optimization of key variables such as dosage, route, vector design, and boosting strategies (37). Most simply, elevated evidence of antitumor immunity has been demonstrated using first tumor antigen were undetectable or weak (Figs. 3 and 4). Thus, little noted, no antibody or T-cell responses against carcinoembryonic antigens were detected. This latter result is analogous to the present study, in which immune responses against the foreign component of the vaccine were frequently induced, yet responses to the relevant tumor antigen were undetectable or weak (Figs. 3 and 4). Thus, little evidence of antitumor immunity has been demonstrated using first generation tumor antigen DNA vaccines.

The method and route of injection also greatly influences the efficacy of DNA vaccines. The i.m. needle injection appears to be the least efficient, whereas needle-free jet injection (Biojector) can improve the immunogenicity of a given DNA vaccine dose (28, 29). Delivery of DNA to the epidermis by gold particle bombardment also required to provide protection of primates against a simian immunodeficiency virus challenge.

ACKNOWLEDGMENTS

We thank Dr. Richard Stout of Bioject for use of the Biojector 2000.

REFERENCES


\(^{6}\) F. Stevenson, personal communication.
Immunogenicity of a Plasmid DNA Vaccine Encoding Chimeric Idiotype in Patients with B-Cell Lymphoma


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