Improving T cell therapy for relapsed EBV-negative Hodgkin’s Lymphoma by targeting upregulated MAGE-A4

Shortened Running Title: MAGE-A4 T cell therapy for Hodgkin’s Lymphoma

Authors and Affiliations: Conrad R. Cruz¹, Ulrike Gerdemann¹, Ann M. Leen¹, Jessica A. Shafer¹, Stephanie Ku¹, Benjamin Tzou¹, Terzah M. Horton², Amanda Copeland³, Anas Younes³, Cliona M. Rooney¹, Helen E. Heslop¹, Catherine M. Bollard¹

¹Center for Cell and Gene Therapy, Baylor College of Medicine, Texas Children’s Hospital, The Methodist Hospital, Houston, Texas, ²Department of Pediatrics, Baylor College of Medicine, Houston, Texas, ³The University of Texas MD Anderson Cancer Center, Houston, Texas

Corresponding Author Information:

Catherine M. Bollard, M.D.
Center for Cell and Gene Therapy
1102 Bates Street Suite 1750
Houston, Texas 77030 USA
Phone: 832-824-4781
Fax: 832-825-4732
Email: cmbollar@txch.org

Author Financial Support: NIH SPORE Grant P50CA126752 AND Specialized Center of Research Award from Leukemia & Lymphoma Society; CRYC - Bear Necessities Pediatric Cancer Foundation & Cancer Prevention Research Institute of Texas; UG – Leukemia & Lymphoma Society; CMB – Leukemia & Lymphoma Society, Gillson Longenbaugh Foundation, & Carl C. Anderson, Sr. and Marie Jo Anderson Charitable Foundation

Keywords: T cell immunotherapy, relapsed Hodgkin’s Lymphoma, MAGE-A4, decitabine, epigenetic modification of tumors, cancer testis antigens
TRANSLATIONAL RELEVANCE

A subset of patients with Hodgkin’s lymphoma (HL) still relapses after conventional therapies and presents with a poor prognosis. Several new treatments are being investigated for this group, and some – like T cell immunotherapy – have shown great promise. Each therapy will, however, remain limited by inherent difficulties: in the case of EBV-specific T cells, the absence of the relevant antigen in most patients is a constraint on otherwise encouraging results. Choosing a different target antigen will inevitably present similar obstacles; a synergistic second therapy is thus needed. Epigenetic-modifying drugs have been shown to upregulate tumor antigen expression. Exploring combinations of new therapies anticipated to have a better safety profile – while maintaining the multimodality approach (the hallmark of successful cancer therapy), should provide adequate alternatives to current regimens. This study validates such a therapy applicable to both autologous and allogeneic HSCT recipients.
ABSTRACT

Rationale: Patients with Hodgkin’s Lymphoma (HL) relapsing after hematopoietic stem cell transplant (HSCT) have limited options for long-term cure. We have shown that infused cytotoxic T cells (CTL) targeting Epstein Barr virus (EBV)-derived proteins induced complete remissions in EBV+ HL patients. A limitation of this approach is that up to 70% of relapsed HL tumors are EBV-negative. For these patients an alternative is to target the cancer/testis antigen MAGE-A4 present in EBV antigen-negative HL tumors. Furthermore, epigenetic modification by clinically available demethylating agents can enhance MAGE-A4 expression in previously MAGE-negative tumors.

Experimental Design: We explored the feasibility of combining adoptive T cell therapy with epigenetic modification of tumor antigen expression. We further characterized MAGE-A4-specific T cell phenotype and function, and examined the effects of the epigenetic-modifying drug decitabine on these T cells.

Results: Cytotoxic T cells were generated specifically recognizing MAGE-A4 expressed by autologous HL targets and tumor cell lines. Decitabine – previously shown to increase tumor antigen expression in Hodgkin’s Lymphoma – did not compromise MAGE-A4 specific T cell phenotype and function. In patients treated with decitabine, expanded MAGE-A4 specific T cells had a broader anti tumor T cell repertoire consistent with increased antigen stimulation in vivo.

Conclusions: Adoptive transfer of MAGE-A4 specific T cells, combined with epigenetic-modifying drugs to increase expression of the protein may improve treatment of relapsed Hodgkin’s Lymphoma.
INTRODUCTION

While the majority of patients with Hodgkin’s Lymphoma (HL) respond favorably to conventional chemotherapy and radiotherapy, an appreciable number relapse (1). For patients relapsing after autologous and/or allogeneic hematopoietic stem cell transplantation (HSCT) (2), the prognosis is especially poor. Moreover, the current success in HL treatment is balanced by the fact that many long-term survivors develop life-threatening complications such as secondary malignancies and cardiac toxicities (3, 4).

An attractive option to reduce the toxicity of standard therapy is to use tumor-specific T cells as adoptive immunotherapy to augment the host response against the tumor cells. About 30% of HL expresses EBV antigens that are suitable targets for adoptive T cell therapy. T cells specific for the EBV associated proteins LMP1 and LMP2 expand in vivo following infusion, infiltrate tumor sites, decrease viral load, and induce clinical remissions (5, 6). To develop adoptive immunotherapy for the majority of HL patients with relapsed/refractory EBV-negative tumors, however, non-viral tumor associated antigens must be targeted. Potential targets include cancer/testis antigens (CTA) which are particularly attractive because of their selective expression on tumor cells. MAGE-A4, an HL-associated CTA, is expressed only in malignant cells and in immune-privileged germ-line cells (7, 8). Like other members of the MAGE-A family of proteins, it is putatively required by tumors to mediate anti-apoptotic functions by interacting with p53 (9). CTA including MAGE-A4 are under epigenetic control and DNA methyltransferase and histone deacetylase inhibitors, which restore expression of apoptosis and anti-proliferation genes, have shown promise in several malignancies (10-16). We and others have shown that a subset of EBV-negative HL express MAGE-A4, the only member of the MAGE family seen in this malignancy (Supplementary Figure 1, 8), and that MAGE-A4 expression is enhanced by the demethylating agent decitabine (10, 17). Furthermore epigenetic therapy mediates immune recognition...
of tumors by up regulating the expression of tumor-specific antigens like MAGE-A4 (10, 18, 19). Here we validated a combined immune and epigenetic therapy approach to treat relapsed HL. We hypothesized that epigenetic treatment would: (i) upregulate MAGE-A4 expression in malignant cells, (ii) render tumor cells susceptible to the cytolytic effect of MAGE-A4-specific T cells without compromising T cell function and (iii) broaden the tumor-specific immune response in vivo. We show that combining decitabine with adoptive T cell therapy is a feasible and potentially effective immunotherapeutic approach to treating relapsed HL.
METHODS

**Blood Donors and Tumor Cell Lines**

Peripheral blood mononuclear cells (PBMCs) used to generate DCs, CTL lines and PHA blasts were obtained from healthy volunteers and patients with HL after obtaining informed consent on Baylor College of Medicine Institutional Review Board-approved protocols. Umbilical cord blood units were obtained from the MD Anderson Cancer Cord Blood Bank. For *in vivo* immune monitoring studies, blood was collected from patients enrolled under M. D. Anderson Cancer Center IRB approved protocols (# 2007-0536 and 2008-0769, NCT00543582 and NCT00866333, ClinicalTrials.Gov database). The EBV-negative Hodgkin’s Lymphoma cell line L1236 was obtained from DSMZ (Braunschweig, Germany). Cells were maintained in RPMI 1640 with 10% fetal bovine serum (FBS, Invitrogen, Carlsbad, CA) and 2 mM L-glutamine (GlutaMAX, Gibco). The HLA type of L1236 was determined to authenticate this cell line, in accordance with recommendations of the National Institutes of Health.

**Immunohistochemistry**

Patient samples were provided by the Texas Children’s Hospital Pathology Department. Cells suspended in phosphate buffered saline (PBS) were placed on glass slides by cytopsin centrifugation (Shandon Cytospin Cytocentrifuge, Thermo Scientific, Waltham, MA) and immediately fixed by incubating for 15 minutes with 4% paraformaldehyde (BD Biosciences, Franklin Lakes, NJ). Antigen retrieval was achieved by incubating slides in 0.3% Triton X-100 (GIBCO) for 5 minutes and then Digest ALL1 (Zymed, San Francisco, CA) for 10 minutes at 37° C. Endogenous peroxidase activity is blocked in 3% hydrogen peroxide. Immunohistochemistry was done using the Powervision+ kit (ImmunoVision Technologies, Daly City, CA) according to the manufacturer’s instructions. For antigen detection, slides were first incubated in preblock/diluent for 30 minutes as provided in the kit, and then incubated with anti-MAGE-
A antibody – detecting MAGE A4 and other members of the MAGE family of proteins - (Abcam, Cambridge, MA) diluted 1:50 in diluent for 1 hour at room temperature. The final step of detection was done using an anti mouse/anti rabbit HRP polymer provided in the kit and detected using DBA.

Generation of MAGE-A4-specific cytotoxic T cells

Monocyte-derived dendritic cells presenting MAGE-A4 peptides were generated as previously described (20), with some modifications. Briefly, PBMCs were obtained from Ficoll-gradient centrifugation of blood from donors. The same protocol was used for all sources of T cells (healthy donors, Hodgkin’s Lymphoma patients, and umbilical cord blood). CD14-positive cells were selected using magnetic cell sorting as described by the manufacturer (Miltenyi, Bergisch Gladbach, Germany). Cells were then cultured in DC media (CellGenix supplemented with 2 mM GlutaMAX TM-I) (CellGenix USA, Antioch, IL; GlutaMAX, Invitrogen, Carlsbad, CA) with 800U/ml GM-CSF (Sargramostim Leukine, Immunex Corp., Seattle, WA) and 1,000U/ml IL-4 (R&D Systems, Minneapolis, MN) for 5 days. IL-4 and GM-CSF were replenished on day 3. Dendritic cells were matured on day 5 using a maturation cocktail consisting of 800 U/mL GM-CSF, 1000 U/mL IL-4, 10 ng/mL IL-1β, 100 ng/mL IL-6, 10 ng/mL TNF-α (R&D Systems, Minneapolis, MN), and 1 μg/mL PGE2 (Sigma, St. Louis, MO). On day 7, mature DCs were pulsed with an overlapping peptide library spanning the MAGE-A4 protein (JPT Technologies, Berlin, Germany) for an hour. After incubation, DCs were used to stimulate the CD14-negative fraction at a responder: stimulator ratio of 10:1, along with the cytokines IL-7, IL-12 and IL-15 (at concentrations of 10 ng/mL each) in CTL media (50% RPMI 1640, 50% Click’s media, 10% human AB serum, 2 mM GlutaMAX). Subsequent weekly stimulations were performed using MAGE-A4-pulsed DCs as antigen presenting cells, again at responder: stimulator ratios of 10:1 with the addition of twice weekly feeds with the cytokines IL-7 and IL-2 (50 U/mL) during the second stimulation, and IL-2 or IL-15 (5 ng/mL) in subsequent stimulations. In healthy donors (n =12), we performed weekly stimulations for 4 weeks with MAGE-A4
antigen-pulsed dendritic cells. After at least two stimulations, cells were harvested, counted and their phenotype, specificity and function assessed.

**Enzyme Linked Immunospot (ELISpot) Analysis**

Interferon gamma enzyme-linked immunospot (ELISpot) analysis was used to evaluate the specificity of expanded MAGE-A4 T cells in response to peptides (Jerini AG, Berlin, Germany) spanning the entire MAGE-A4 protein. Briefly, plates were coated with anti-interferon capture antibodies, and 1x10^5 cells were plated in each well. Peptide mixes or specific peptides were then added onto cells in duplicates or triplicates. Irrelevant peptides (Aspf16) and staphylococcus enterotoxin B or phytohemaglutinin (PHA) were used as negative and positive controls, respectively. Their ability to elicit an interferon secretory response was then independently assessed by Zellnet Consulting (New York, NY) and compared with input cell numbers to obtain the frequency of tumor-specific T cells.

**Flow Cytometry Phenotyping**

Expanded MAGE-A4-specific T cells were also assessed for surface expression of CD3, CD4, CD8, CD25, CD45RA, CD45RO, CCR7, CD27, CD28, CD69, and CD70 using fluorochrome-conjugated monoclonal antibodies against these proteins (BD Biosciences, Franklin Lakes, New Jersey). T cells were harvested and washed with cold phosphate-buffered saline (1X PBS, Sigma, St. Louis, MO) supplemented with 1% FBS (FBS, Invitrogen, Carlsbad, CA). They were spun down and antibodies were added to the pellets and allowed to bind at 4°C for 20 minutes in the dark. Cells were then washed twice with cold PBS with 1% FBS and acquired on a FACSCalibur flow cytometer. Data was analyzed using Cell Quest software (Becton Dickinson).
**Chromium Release Assay**

MAGE-A4 T cells were tested for selective killing of MAGE-A4 targets using a chromium release cytotoxicity assay. Briefly, \(^{51}\)Cr-labeled target cells (autologous PHA blasts or LCL lines pulsed with the MAGE-A4 peptide mix) were co-cultured with effector cells that have been serially diluted to produce the effector-to-target (E/T) ratios specified in the results. Target cells incubated in complete medium or 1% Triton X-100 (Sigma-Aldrich) were used to determine spontaneous and maximal \(^{51}\)Cr release, respectively. After 4 to 6 hours, supernatants were harvested, and radioactivity was measured on a gamma counter. Mean percentages of specific lysis of triplicate wells were calculated as 100 x (experimental release – spontaneous release)/(maximal release – spontaneous release).

**Incubation of T cells and tumor cells with Decitabine**

In vitro experiments with the demethylating agent decitabine (5’ aza 2’ deoxycytidine) were performed by adding 1 μM of the drug to cultured T cells. For experiments with MAGE-A4 specific T cells, generated cells were cultured in the presence of the drug for 24 hours before assays (flow cytometry and IFN\(\gamma\) ELISpot) were performed.

**Evaluating the tumor specific immune response in HL patients receiving decitabine**

Patients with relapsed and refractory HL enrolled on M. D. Anderson protocol # 2007-0536 were treated with decitabine (75 mg/m\(^2\)) daily x 5 days and oral MGCD-0103 therapy (85 mg fixed dose) for 3 consecutive weeks. Blood for tumor-specific immune analysis was collected pre decitabine, 2 days after completion of decitabine, and following completion of a cycle. Patients enrolled on M. D. Anderson protocol # 2008-0769 received entinostat starting at 10 mg and later increased to 15 mg orally self administered every 2 weeks on 4 week cycles once weekly for three consecutive weeks. Blood for immune analysis was collected pre therapy and 1 week following treatment.
RESULTS

MAGE-A4 specific T cells can be expanded from healthy adult donors for use in adoptive immunotherapy

To determine if MAGE-A4 specific T cells can be successfully expanded from different donor sources, we generated allogeneic T cell lines from healthy adult donors and umbilical cord bloods and evaluated their phenotype and function in vitro. Healthy donor T cells lines, predominantly CD8 cytotoxic T cells (median 57%), and CD4 T helper cells (median 20%) expanded to sufficient numbers for clinical use (Figure 1a,1b). A median of 69% of T cells had a memory (CD45RA-CD45RO+) phenotype while a median of 7% had a naïve phenotype (CD45RA+CCR7+). Median expression of activation molecules was 24% (CD27), 18% (CD69), and 14% (CD70) (Figure 1b). Specificity of the T cell lines was evaluated in IFNγ ELISpot assays. A median response of 78 interferon gamma (IFNγ) spot forming cells (SFC)/1 x 10⁵ cells (mean 152; range 12-635) was observed in response to MAGE-A4 compared to a median of 4 IFNγ SFC/1x10⁵ cells (mean 4; range 0-30) in response to irrelevant peptides (Figure 1c). Both CD4+ and CD8+ T cells contributed to the interferon response (Supplementary Figure 2). Furthermore, generated MAGE-A4 T cells killed MAGE-A4 pulsed autologous targets (PHA blasts), but not non-MAGE-A4 expressing autologous targets (Figure 1d, Table 1) or allogeneic PHA blasts (data not shown). MAGE-A4 T cells also killed HL cell lines expressing MAGE-A4 matched in at least one HLA allele (Figure 1e).

In contrast, it was only possible to expand 4/28 MAGE-A4 specific CTL lines from umbilical cord blood (median 81 IFNγ SFC/1x10⁵ cells; mean 74, range 20-115) for MAGE-A4 versus (median 6 IFNγ SFC; mean 12, range 0-37 for irrelevant peptides) (Supplementary Figure 3). Using overlapping peptide pools, generated as previously described (21) we found that most MAGE-specific T cell lines mapped to 20mer peptide epitopes near the C terminus of the protein. This region contains the majority of previously
published MAGE-A4 T cell epitopes (22-29). Among the HLA A2 donors in our cohort, cytotoxic responses were restricted to the HLA A2 allele (Supplementary Figure 4). We also consistently observed a response against the 20-mer peptide – NPARYEFLWPRALAETSYV (Table 2). Further characterization identified three novel HLA A2 restricted epitopes (YEFLWPRA, EFLWGPRAL, and RALAETSYV) within this region (Figure 1f).

**MAGE-A4 T cells can be generated from Hodgkin’s Lymphoma patients**

Although relapsed HL patients typically have low blood counts, T cells specific for MAGE-A4 can be expanded from HL patients. These cells phenotypically resembled T cell lines expanded from healthy donors (Figure 2a). In T cells expanded from the peripheral blood of patients with HL (n=9) a median 244 SFC/1x10⁵ cells (mean 296; range 32-1031) responded to MAGE-A4 peptides compared to a mean of 5 SFC/1x10⁵ cells (mean 1.5; range 1-11) responding to irrelevant targets (Figure 2b). We also mapped HL patient responses to identified 20mer epitopes and generated these epitope-specific T cells (Table 3). Additionally, specific killing of MAGE-A4-pulsed autologous targets (but no non-pulsed autologous targets) was seen in cytotoxicity assays (Figure 2c).

**Decitabine has minimal effects on MAGE-A4 T cell phenotype and function**

We studied the effects of decitabine in vitro on the MAGE-A4 specific T cells. Cell viability, measured by trypan blue exclusion assays, showed a slight decrease in cell numbers (approximately 80%, data not shown) following culture with decitabine. Importantly, however, treatment of the T cells with 1 μM decitabine for 24 hours did not affect surface marker expression (Figure 3a) or IFNγ release by expanded T cells (Figure 3b) in response to MAGE-A4 peptides.
**Patients with relapsed HL receiving epigenetic modifying agents have increased frequencies of MAGE-A4 T cells**

To evaluate the in vivo effects of decitabine on tumor antigen specific T cells, patient samples were obtained before and after treatment with epigenetic-modifying drugs that included HDAC inhibitors with or without decitabine. We hypothesized that the tumor-specific T cell immune response would show a broader epitope specific T cell response or an increased cytokine response (signifying an increase in the frequency of antigen-specific T cells). In patients receiving a decitabine containing regimen with a clinical responses on PET scan, MAGE-specific T cells recognized a broader number of MAGE-A4 epitopes (**Figure 4a**) and increased secretion of interferon gamma in response to MAGE-A4 antigens (**Figure 4b**) after decitabine treatment. In patients not receiving a decitabine containing regimen, interferon gamma response was decreased (**Figure 4c and 4d**). In other patients, no improvement in T cell reactivity to MAGE-A4 antigen was observed (data not shown) following treatment with epigenetic modifying drugs, suggesting that although decitabine may modulate immune function, the presence of other agents may limit endogenous T cell responses to tumor antigens. These results support combining adoptive T cell therapy with decitabine to upregulate CTA expression in HL relapsing after HSCT.
DISCUSSION

Previous observations by our group showed that T cells targeting antigens expressed on malignant cells in relapsed HL mediate clinical improvement (5) supporting the possibility that T cells recognizing CTAs target a subset of cells that are more resistant to traditional cytotoxic therapies (10). Epigenetic-modifying drugs enhance tumor antigen expression and improve the cytotoxicity of antigen-specific T cells (10). Based on these findings, we validate here an approach to improve the immunotherapeutic potential of such adoptive T cell therapy by combining it with decitabine. We successfully expanded MAGE-A4 specific CD8+ and CD4+ T cells from healthy donors and HL patients and showed that decitabine did not restrict specificity or function of polyclonal T cell populations against MAGE-A4 targets in vitro.

In contrast to studies that have focused on single HLA-restricted epitopes to generate MAGE-A4 specific T cells (21, 22), the peptide mixture we used elicits a broad T cell response. Using potent dendritic cells as antigen presenting cells permitted the expansion of antigen-specific T cells from HL patients for autologous use. We also evaluated the feasibility of combining decitabine with T cell immunotherapy for relapsed HL and observed for the first time that tumor-specific T cells were largely unaffected by the presence of drug.

MAGE-A4 is an attractive target antigen since it is expressed by HL Reed Sternberg cells, subject to epigenetic regulation (7) (Supplementary Figure 1) and upregulated by DNA methyltransferase inhibitors like decitabine (10, 23). Such MAGE-A4 upregulation by Reed Sternberg should enhance tumor-specific T cell killing. Furthermore MAGE-A proteins may reduce malignant potential by inhibiting the tumor suppressor p53 (9, 24). Finally, MAGE is expressed in a variety of malignancies (25-27),
opening the possibility of extending this immunotherapeutic strategy to other hematological malignancies and tumors.

The practical applicability of target antigens for immunotherapy depends on their immunogenicity and the ability to expand cells from as many donor sources as possible. HSCT is a common setting for adoptive transfer of either recipient or allogeneic donor T cells. Our MAGE-A4 specific T cell expansion strategy is applicable for both donors and HL patients, even following immunosuppressive salvage high-dose chemotherapy and autologous HSCT and despite the potential immunomodulatory effect of Reed-Sternberg cells which produce cytokines that skew T helper cells towards a Th2 phenotype and can mediate T cell apoptosis (1, 28, 29).

Umbilical cord blood is an emerging source of donor cells for HSCT, particularly useful for underrepresented minorities and child recipients. Cord blood T cells have lower cytotoxic ability, as well as greater rates of activation-induced cell death (30, 31), and the generation of MAGE-A4 T cells from cord blood still presents a challenge for translation to the clinic. Although we successfully primed MAGE-specific T cells from cord blood, the procedure was not robust with only 14% of the expanded CTL lines showing specificity for MAGE-A4. This contrasts with our ability to reliably expanded virus-specific T cells from umbilical cord blood (32, 33). The disparity may lie in the nature of the target antigen. Since cancer/testis antigens like MAGE-A4 are expressed in the placenta (34), the constant interaction with umbilical cord blood T cells in a highly tolerogenic environment may contribute to the lack of response to CTA.

The percentage of tumor cells expressing the target antigen can limit the success of immunotherapy. Since a single tumor target antigen is unlikely to be sufficient some investigators have targeting multiple
tumor antigens (35). An alternative and complementary strategy is to increase expression of target antigens in vivo using epigenetic-modifying drugs (36, 37) which upregulate CTA expression (38, 39).

Epigenetic-modifying drugs have synergistic effects on the immune system: enhanced T cell responses occur in AML and myelodysplastic patients after treatment with decitabine (19), while a decitabine-induced increase in Tregs may prevent GVHD without affecting the graft versus tumor effect (40). Although the effects of demethylating agents on tumor cells have been extensively studied (11, 13), effects of these drugs on the T cell effectors has not been explored. A murine transplant study suggests that T cells are actively inhibited and inactivated by these agents (41) but these observations may not be applicable to the adoptive transfer of ex vivo expanded antigen-specific T cells following epigenetic drug treatment. Our results show that epigenetic drugs in concentrations exceeding expected treatment levels does not adversely affect the phenotype and function of MAGE-A4 specific T cells in vitro, and should not reduce efficacy of the adoptively transferred cells in vivo. Although we observed an inhibition of proliferation and the abrogation of antigen specificity at continued exposures to higher >200ng/ml (>1 μM) concentrations of decitabine, as well as cells exposed to longer term (>24 hour) culture with decitabine, such a situation would not occur in vivo. Pharmacokinetic studies of AML and MDS patients receiving decitabine describe maximum plasma concentrations of only 64-77 ng/mL (42). Moreover, we plan to administer T cells after decitabine treatment, circumventing the effect of prolonged exposure to the drug in the clinical setting.

We showed that patients with relapsed HL achieving clinical responses after decitabine also had enhanced MAGE-specific T cell responses in vivo. However, although improved T cell responses were seen following the administration of decitabine/HDACi regimens, this effect was not seen in patients who received HDACi therapy alone. A variety of reasons can be postulated for this discrepancy, including
the more pleiotropic effects of histone deacetylase inhibitors which affect chromatin structure and interfere with the antigen presenting machinery (43). Further, the two classes of epigenetic modifying drugs target different genes in T cells, with one class effectively activating T cells while another suppresses them. The epigenetic modification of gene expression, while mediated by both DNA methyltransferase inhibitors and histone deacetylase inhibitors, appears to have inherent gene restrictions through mechanisms that remain incompletely understood. It is likely that targets for DNA methyltransferase and HDAC inhibitors differ in T cells, although they mediate similar anti-tumor effects in malignant cells. DNA methyltransferase inhibitors, for example, appear to mediate a pro-inflammatory response by activating Th1 cells (44), while HDAC inhibitors result in opposite effects thus limiting Th1 effector cell functions (45). Additionally, regulatory T cell (Treg) induced immune suppression, is differentially affected by these classes of epigenetic-modifying drugs. Decitabine has been reported to limit FOXP3 expression (46) while HDAC inhibitors enhance FOXP3+ Treg-mediated suppressive activity (47).

One caveat to our findings is that epigenetic modification could have an impact on the autologous APC used in their in vitro expansion. We did not address the effect of epigenetic modification on antigen presenting cells and few studies have explored this possibility. One study (48) suggests that tumor-infiltrating myeloid cells exposed to decitabine, differentiate into mature MHC class II-expressing dendritic cells. Another study reports that antigen processing and presentation are unaffected by treatment with histone deacetylase inhibitors (46). Nevertheless, to our knowledge, this is the first demonstration of the validity of using decitabine to enhance the tumor-specific T cell immune response in patients with relapsed HL. Results support the initiation of larger studies to correlate enhanced tumor-specific immune responses with clinical response. Whether this effect is limited to MAGE A4 or is also applicable to a host of other antigens (viral antigens and other tumor antigens) is still to be
determined since the present study is limited by the small cell numbers we obtained from these heavily pre treated patients.

The lack of endogenous T cells in Hodgkin’s Lymphoma patients following chemotherapy (49) highlights the rationale for combining adoptive T cell therapy with epigenetic-modifying drugs. While we successfully generated MAGE-A4 specific T cells from nine HL patients, no response occurred in other patients tested (data not shown). Peripheral blood mononuclear cell and dendritic cell numbers were reduced and T cells from these patients failed to expand after several stimulations, consistent with the profound immune deficiency frequently seen in HL patients (49).

In conclusion our results highlight the important synergistic role that adoptively transferred tumor-specific T cells could play with decitabine in the control of relapsed HL. Targeted immune based treatment is a promising strategy for patients with HL to avoid the need for combination radiation and chemotherapy which carry the risk of unacceptable long term effects (4).
GRANT SUPPORT

This work was supported in parts by NIH SPORE Grant P50CA126752 and a Specialized Center of Research Award from the Leukemia Lymphoma Society. CRYC was also supported by the Bear Necessities Pediatric Cancer Foundation and the Cancer Prevention Research Institute of Texas. UG was supported by the Leukemia and Lymphoma Society. CMB was also supported by a career development award from the Leukemia Lymphoma Society and awards from the Gillson Longenbaugh Foundation and the Carl C. Anderson, Sr. and Marie Jo Anderson Charitable Foundation.
REFERENCES CITED


LIST OF TABLES AND FIGURES

TABLE 1. Cytolytic ability of 8 other donors is shown by their ability to lyse MAGE-A4-pulsed autologous targets. Specific lysis was evaluated by standard Cr⁵¹ release assay, shown is the E:T ratio at 20:1.

TABLE 2. Responses of healthy donor-derived T cells to MAGE-A4 were mapped to 20mer regions of the protein. Listed are the donors with their corresponding HLA types and 20mer regions recognized.

TABLE 3. Responses of Hodgkin’s lymphoma patient-derived T cells to MAGE-A4 were mapped to 20mer regions of the protein.

FIGURE 1. Generation of MAGE-A4 specific T cells from healthy donors. A). Expansion of MAGE specific T cells after 2 stimulations with MAGE pulsed antigen presenting cells. Fold change was calculated from weekly cell counts using the trypan blue exclusion method. B). Phenotype of CD3+ cells after at least 2 stimulations was determined using flow cytometry of surface receptors listed on the x-axis. The median is shown in black bars. C). Shows the specificity of MAGE-specific CTL lines generated from 15 donors as measured by IFNγ release (IFNyELIspot) in response to stimulation with MAGE-A4 pepmix. Results are expressed as SFC/1x10⁵ input cells. Control was IFNγ release in response to stimulation with irrelevant pepmix. The black bars show the median interferon gamma secretion. CTL lines were able to kill MAGE-loaded autologous PHA blasts. D). and HLA A2 matched MAGE positive HL cell line L1236. E). Specific lysis was evaluated by standard Cr⁵¹ release assay - E:T ratio of 40:1, 20:1, 10:1 and 5:1. F). Further epitope mapping of the NPARYEFLWGPRALAETSYV 20mer commonly seen in A2+ donors show that 3 donors each recognize a unique and distinct 9mer epitopes as shown using IFNγ ELISPOT assay. Results are expressed as SFC/1x105 input cells +/- SD.
FIGURE 2: Generation of MAGE-A4 T cells from patients with Hodgkin’s lymphoma. A). Phenotype analysis of cells obtained using flow cytometry are shown and are similar to the phenotype of CTL derived from healthy donors. Black bars show the median percentage for each marker. B). Specificity of the CTL was evaluated by IFNγ ELISpot assay. CTL responses to MAGE-A4 pepmix versus irrelevant pepmix are shown. Data from nine HL patients is shown. IFNγ positive Spot Forming Cells (SFC)/1x10^5 input cells are shown for each CTL line. The black bars show the median interferon gamma secretion for each group. C). Cytolytic activity of evaluable T cell lines generated from Hodgkin’s lymphoma patients is evaluated using autologous PHA blasts pulsed with the MAGE-A4 peptide mix as targets in a chromium release assay.

FIGURE 3: MAGE specific T cell phenotype and function are unaffected by Decitabine. A). Phenotype of the MAGE-specific T cells pre and post treatment with 5’aza-2’deoxycytidine is shown. B). T cell secretion of interferon-gamma in response to MAGE-A4 peptides is shown pre and post decitabine treatment. Black bars indicate the IFNγ response in CTL lines incubated with decitabine (gray bars) versus without decitabine (black bars).

FIGURE 4: Increased frequency of MAGE-A4 specific T cells in vivo in patients receiving a regimen containing decitabine. T cells obtained from the peripheral blood of HL patients taken before and after treatment with an HDAC inhibitor with or without decitabine were expanded in vitro, and MAGE specific responses were evaluated in an IFNγ ELISpot assay. Results are shown for patients who received decitabine containing regimens (A and B) versus those who did not (C and D).
Table 1

<table>
<thead>
<tr>
<th>Donor</th>
<th>% Killing Irrelevant Target</th>
<th>% Killing MAGE-A4-Pulsed Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.70%</td>
<td>40.35%</td>
</tr>
<tr>
<td>3</td>
<td>7.22%</td>
<td>19.44%</td>
</tr>
<tr>
<td>4</td>
<td>1.1%</td>
<td>21.5%</td>
</tr>
<tr>
<td>5</td>
<td>8.00%</td>
<td>40.30%</td>
</tr>
<tr>
<td>8</td>
<td>3.8%</td>
<td>24.7%</td>
</tr>
<tr>
<td>9</td>
<td>9.3%</td>
<td>24.13%</td>
</tr>
<tr>
<td>10</td>
<td>7.10%</td>
<td>20.4%</td>
</tr>
<tr>
<td>13</td>
<td>0.6%</td>
<td>10.36%</td>
</tr>
</tbody>
</table>
Table 2

<table>
<thead>
<tr>
<th>Donor</th>
<th>HLA Type</th>
<th>Peptide Recognized</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A2, A24, B8, B65</td>
<td>SASEEEIWEELGVMGVYDGR</td>
</tr>
<tr>
<td>2</td>
<td>A2, A26, B15, B44</td>
<td>NPARYEFLWGPRLAETSYV</td>
</tr>
<tr>
<td>3</td>
<td>A2, B7, B40</td>
<td>NPARYEFLWGPRLAETSYV</td>
</tr>
<tr>
<td>4</td>
<td>A3, A24, B40, B44</td>
<td>NPARYEFLWGPRLAETSYV</td>
</tr>
<tr>
<td>5</td>
<td>A1, A11, B8, B49</td>
<td>ETSYVKLEHVVRVNARVRIAYPSL</td>
</tr>
<tr>
<td>6</td>
<td>A2, B7, B40</td>
<td>NPARYEFLWGPRLAETSYV</td>
</tr>
<tr>
<td>7</td>
<td>A2, B60, B61</td>
<td>NPARYEFLWGPRLAETSYV</td>
</tr>
<tr>
<td>8</td>
<td>A3, A24, B8, B35</td>
<td>KVLEHVVRVNARVRIAYPSL</td>
</tr>
<tr>
<td>9</td>
<td>A1, A3, B8, B35</td>
<td>AYPSLAYPSLREAALLLLLEE</td>
</tr>
<tr>
<td>11</td>
<td>---</td>
<td>IFPKTGLLLIVLGTIAMEGD</td>
</tr>
<tr>
<td>12</td>
<td>---</td>
<td>ELAHFLRYRAKELVTKAE</td>
</tr>
<tr>
<td>13</td>
<td>---</td>
<td>LEEVPAAESAGPPQSPQGAS</td>
</tr>
<tr>
<td>14</td>
<td>---</td>
<td>SNKVDELAHFLRKYRAKELVTKAE</td>
</tr>
<tr>
<td>15</td>
<td>A3, A33, B14, B38</td>
<td>PRALAETSYVKLEHVVRVN</td>
</tr>
</tbody>
</table>
Table 3

<table>
<thead>
<tr>
<th>Patient</th>
<th>Peptide Recognized</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IKNYKRCFPVIFGKASESLK</td>
</tr>
<tr>
<td>2</td>
<td>NPARYEFLWGPRALAESYV</td>
</tr>
<tr>
<td>3</td>
<td>ETSYVKVLEHVVRVNARVRIKVLEHVVRVNARVRIAYPSL</td>
</tr>
<tr>
<td>4</td>
<td>SASEEIEWEELGVMGVYDGR</td>
</tr>
<tr>
<td>5</td>
<td>QVPGSNPARYEFLWGPRALA QVPGSNPARYEFLWGPRALAETSYV</td>
</tr>
<tr>
<td>6</td>
<td>IFGKASESLKMIFGIDVKEV SESLMIFGIDVKEVDPTSN</td>
</tr>
<tr>
<td>7</td>
<td>VTKAEMLERVIKNYKRCFPV MLERVIKNYKRCFPVIFGKA</td>
</tr>
<tr>
<td>8</td>
<td>SASEEIEWEELGVMGVYDGR</td>
</tr>
</tbody>
</table>
Figure 3

A

% CD3

CD4+, CD8+, CD4+CD25+, CD45RA+/CCR7+, CD45RO+/CD45RA-, CD70+, CD70+ CD27, CD28, CD69+

- no decitabine
- + 1 uM decitabine
- no decitabine – median
- + 1 uM decitabine - median

B

IFNγ SFC/1x10^5 Cells

No Decitabine
+ 1 uM Decitabine

D2, D3, D5, D8, D7, D2, D3, D5, D8, D7

Irrelevant target, MAGE-A1
Improving T cell therapy for relapsed EBV negative Hodgkins Lymphoma by targeting upregulated MAGE-A4

Conrad Russell Y Cruz, Ulrike Gerdemann, Ann M Leen, et al.

Clin Cancer Res  Published OnlineFirst September 9, 2011.