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Antibody Targeting to a Class I MHC-Peptide Epitope Promotes Tumor Cell Death

Vaughan P. Wittman,*† David Woodburn,† Tiffany Nguyen,† Francisca A. Neethling,† Stephen Wright,‡ and Jon A. Weidanz¹*†

Therapeutic mAbs that target tumor-associated Ags on the surface of malignant cells have proven to be an effective and specific option for the treatment of certain cancers. However, many of these protein markers of carcinogenesis are not expressed on the cells’ surface. Instead these tumor-associated Ags are processed into peptides that are presented at the cell surface, in the context of MHC class I molecules, where they become targets for T cells. To tap this vast source of tumor Ags, we generated a murine IgG2a mAb, 3.2G1, endowed with TCR-like binding specificity for peptide-HLA-A*0201 (HLA-A2) complex and designated this class of Ab as TCR mimics (TCRm). The 3.2G1 TCRm recognizes the GVL peptide (GVLPALPQV) from human chorionic gonadotropin β presented by the peptide-HLA-A*0201 complex. When used in immunofluorescent staining reactions using GVL peptide-loaded T2 cells, the 3.2G1 TCRm specifically stained the cells in a peptide and Ab concentration-dependent manner. Staining intensity correlated with the extent of cell lysis by complement-dependent cytotoxicity (CDC), and a peptide concentration-dependent threshold level existed for the CDC reaction. Staining of human tumor lines demonstrated that 3.2G1 TCRm was able to recognize endogenously processed peptide and that the breast cancer cell line MDA-MB-231 highly expressed the target epitope. The 3.2G1 TCRm-mediated CDC and Ab-dependent cellular cytotoxicity of a human breast carcinoma line in vitro and inhibited in vivo tumor implantation and growth in nude mice. These results provide validation for the development of novel TCRm therapeutic reagents that specifically target and kill tumors via recognition and binding to MHC-peptide epitopes. The Journal of Immunology, 2006, 177: 4187–4195.
have been used to demonstrate the presence of hCGβ in lung, gynecological, and head and neck cancers. The aggressiveness and resistance to therapy of bladder cell carcinoma expressing hCGβ has been associated with an autocrine anti-apoptotic effect elicited by the free β-chain (18). A series of Abs that bind hCG were developed for use as diagnostic reagents and hCGβ-specific Abs, which have application in pregnancy testing as well as monitoring for hCG positive tumors continue to be developed (19). An anti-hCGβ vaccine (for use in treatment of human cancer) that targets hCGβ to dendritic cells has been shown to elicit both cytotoxic and helper T cell responses to peptide pulsed target cells and tumor cell lines (20). Recently, several MHC-I epitopes from hCGβ have been identified which bind with high affinity to HLA-A*0201 molecules (21).

A first step in evaluating the efficacy of therapeutic Abs is in vitro assessment of their specificity and ability to induce tumor cell lysis via the activation of complement and ADCC. The therapeutic successes of the mAbs trastuzumab and rituxamab are thought to correspond to peptide pulsed target cells and tumor cell lines (20). In this report, we investigate the Ag binding specificity, in vitro lytic capabilities and in vivo tumor growth inhibition of a TCRm mAb, 3.2G1, which is specific for the GVL peptide (residues 47–55 from hCGβ) presented in the context of HLA-A2.

Materials and Methods

Cell lines and Abs

The human tumor cell lines T2 (lymphoblast), SW620 (colon), MDA-MB-231 (breast) and BT20 (breast) were obtained from the American Type Culture Collection. The SKOV3.A2 (ovarian) transfectant was a gift from Dr. V. Ramakrishna (Celldex Therapeutics). The hybridoma cell line BB7.2 that produces the BB7.2 mAb (specific for the α2 domain of properly folded HLA-A2) was purchased from the ATCC. The pan HLA-A,B,C Ab W6/32, which recognizes only appropriately assembled HLA-β2-microglobulin-β2m complexes, was a gift from Dr. R. Buchli (Pierce Protein).

The murine IgG2a and IgG1 isotype control Abs UPC-10 and MOPC 21, respectively, were purchased from Sigma-Aldrich. Other anti-murine Abs that were used for analysis or ELISA were purchased as part of a mouse Ig panel or the SBA Clonotyping System/HRP from Southern Biotechnology Associates. Goat anti-mouse secondary Abs used for cell staining included the Fcγ-specific FITC-labeled F(ab’)_2, and the Fcγ (1 + 2a + 2b + 3)-specific PE-labeled Ig from Jackson ImmunoResearch Laboratories.

The murine IgG2a and IgG2a standard supplied by the manufacturer. Development, quenching, and analysis of the plate were performed as described above for the TCRm Abs by ELISA as described below.

ELISA

ELISA was performed using Maxisorb 96-well plates (Nunc). Assays to evaluate binding specificity of the TCRm Abs were done on plates coated with either HLA monomer (500 ng per well) or HLA tetramer (100 ng/well). Bound Abs were detected with peroxidase-labeled goat anti-mouse IgG (Jackson ImmunoResearch Laboratories) followed by ABTS (Pierce). Reactions were quenched with 1% SDS. Absorbance was measured at 405 nm on a Victor II plate reader (PerkinElmer). The SBA clonotyping system/HRP and mouse Ig panel from Southern Biotechnology Associates were used to estimate the concentration of 3.2G1 (isotype IgG2a) in the supernatant of FBS-containing medium. The assay was run according to the manufacturer’s directions, and 3.2G1 signal was compared with that of an IgG2a standard supplied by the manufacturer. Development, quenching, and analysis of the plate were performed as described above for the TCRm Abs.

Cell culture

Cell culture medium included IMDM and RPMI 1640 from Cambrex, L-15 from Mediatech, and Flexibroth SFM and L-15 from Invitrogen Life Technologies. Medium supplements included heat-inactivated FBS and penicillin/streptomycin from Sigma-Aldrich and 1-glutamine from HyClone. Recombinant human IL-2 was obtained from PeproTech. All tumor lines were maintained in culture medium containing glutamine, penicillin/ streptomycin, and 10% FBS. Cell cultures were maintained at 37°C in 5% CO₂ atmosphere, with the exception of MDA and SW620, which were cultured without CO₂. MDA and SW620 cells were cultured in L-15, SKOV3.A2, and T2 in IMDM, and BT20 in RPMI 1640 medium. When necessary, attached cells were released from flasks using TrypLE Express (Invitrogen Life Technologies).

Human PBMC from anonymous donors were obtained from separation cones of discarded apheresis units from the Coffee Memorial Blood Bank (Amarillo, TX) after platelet harvest. Cells were separated on a Ficoll gradient, then washed, counted, and resuspended in AIM-V medium containing 200 U/ml IL-2 per a concentration of 2–2.5 × 10⁶ cells/ml. PBMC were maintained at this concentration with medium changes and addition of IL-2 every 2–3 days for a maximum of 7 days. These conditions have been shown to maintain and activate resident NK cells within the PBMC population (25).

Murine hybridoma cells were initially grown in RPMI 1640 medium supplemented with 10% FBS, glutamine, and penicillin/streptavadin (RPMI/10) as described below. After selection for binding specificity, clones were grown in RPMI/10 to provide supernatant containing the Abs of interest or in serum-free medium to provide supernatant for isolation of purified Abs from protein G columns (GE Healthcare BioSciences).

Pepitides and HLA-A2 complexes

The following peptides were synthesized at the Molecular Biology Resource Facility, University of Oklahoma (Oklahoma City, OK.): KIFGSLAFL (residues 369–377, designated Her-2), eukaryotic translation factor 4 γ VLMTEDIKL (residues 720–728, designated eIF4G), human chorionic gonadotropin-β TMTRVLQGV (residues 40–48, designated TMT), VLGVPFAL (residues 44–53, designated VLQ), and GVLFALPQQV (residues 47–55, designated GVL). HLA-A2 extracellular domain and β2m were produced as inclusion bodies in Esherichia coli and refolded essentially as described previously (26). After refolding, the peptide-HLA-A2 mixture was concentrated and properly folded complex was isolated from contaminants on a Superdex 75 sizing column (GE Healthcare BioSciences AB). This complex, designated the monomer, was biotinylated using the BirA biotin ligase enzyme (Avidity) and purified on a 575 column. Purified, human-tumor monomer was mixed with streptavidin at an empirically determined ratio to yield higher-order complexes. Complexes were then separated on a Superdex 200 column, and the peak corresponding to a streptavidin plus four monomers (the tetramer) was isolated. Tetramer concentration was determined by BCA protein assay (Pierce).

Generation of anti-GVL/A2 TCRm mAbs

Mice (BALB/c; The Jackson Laboratory) were immunized s.c. with a solution containing 50 µg of purified HLA-A2-hCGβ-hCGV peptide (designated GVL/A2) complex and Quil-A adjuvant (Sigma-Aldrich) at 15-day intervals. One week after the third immunization, splenocytes were obtained from mice with the P3X63.Ag8.653 myeloma cell line using a Clonacell-HY Kit (StemCell Technologies). After 2 wk in semisolid medium, single colonies were picked, transferred to 96-well tissue culture plates, and grown for 3–4 days in Clonacell Medium E. Supernatants were tested for the appropriate mAb production by ELISA as described below.

ELISA

ELISA was performed using Maxisorb 96-well plates (Nunc). Assays to evaluate binding specificity of the TCRm Abs were done on plates coated with either HLA monomer (500 ng per well) or HLA tetramer (100 ng/well). Bound Abs were detected with peroxidase-labeled goat anti-mouse IgG (Jackson ImmunoResearch Laboratories) followed by ABTS (Pierce). Reactions were quenched with 1% SDS. Absorbance was measured at 405 nm on a Victor II plate reader (PerkinElmer). The SBA clonotyping system/HRP and mouse Ig panel from Southern Biotechnology Associates were used to estimate the concentration of 3.2G1 (isotype IgG2a) in the supernatant of FBS-containing medium. The assay was run according to the manufacturer’s directions, and 3.2G1 signal was compared with that of an IgG2a standard supplied by the manufacturer. Development, quenching, and analysis of the plate were performed as described above for the TCRm Abs.

Cell staining

T2 cells were pulsed with the peptides at 20 µg/ml for 4 h in growth medium, with the exception of the peptide-translation experiments in which the peptide concentration was varied as indicated. Cells were washed and resuspended in staining buffer (SB) (PBS plus 0.5% BSA plus 2 mM EDTA) and then stained with 1 µg of 3.2G1, BB7.2, or isotype control Ab for 15–30 min in 100 µl of SB. Cells were then washed with 3 ml SB and the pellet was resuspended in 100 µl of SB containing 2 µl of either of two goat anti-mouse secondary Abs (FITC or PE labeled). After incubating for 15–30 min at room temperature, the wash was repeated, and cells were resuspended in 0.5 ml SB, analyzed on a FACScan instrument (BD Biosciences) and evaluated using CellQuest software (BD Biosciences). Tumor cell lines were stained and evaluated in the same manner as the T2 cells after being released from plates and washed in SB. Tetramer competition stains were conducted in the same order described above, except that tetramer at the appropriate concentration was mixed with the Ab and allowed to stand for 40 min before the mix was added to the cells.

Cytotoxicity analysis

Specific cell lysis in the CDC, NK cell, and ADCC assays was evaluated using the Cytotox 96 nonradioactive cytotoxicity lactate dehydrogenase (LDH) assay (Promega) following the instructions provided by the manufacturer. This assay measures the release of cellular LDH into the culture supernatant after cell lysis. All cells were grown or pulsed with peptide in
their appropriate growth medium, but final incubations of cells in the presence of complement (CDC) or human PBMCs (NK and ADCC) was conducted in AIM-V medium for 4 h at 37°C. CDC analysis of T2 cells took place under three different conditions: the Ab concentration was varied and competing or noncompeting tetramer added (1), peptide mixes were used to pulse cells (2), or GVL peptide was titrated for use in cell pulsing (3). CDC analysis of MDA-MB-231 cells using Ab dilutions and tetramer competition was conducted on adherent cells. Exact conditions are described in the figure legends and/or Results. Standard complement or LoTox complement was obtained from Cedarlane Laboratories. All cells used as targets for cytotoxicity assays were puls ed for 4 h with peptide. Specific lysis in the CDC assays was calculated as follows: (specific release − spontaneous release) / (maximum release − spontaneous release) × 100 = specific release. ADCC reactions using human PBMC effector cells were conducted on MDA-MB-231 target cells using 3.2G1 or W6/32 Abs at a final concentration of 10 μg/ml. E:T ratios were varied as indicated in the figures. NK analysis was performed by mixing human E with K562 cells and incubating as above. Specific lysis in ADCC analysis was calculated as follows: ([E + T + Ab release] − [E + T] − Ab release) / (maximum release − spontaneous release) × 100 = specific release. Specific lysis in NK analysis was calculated: ([E + T release − spontaneous release]) / (maximum release − spontaneous release) × 100 = specific release. Spontaneous and maximum release were measured before and after, respectively, lysis of target cells with 0.9% Triton X-100.

In vivo studies

Athymic nude mice (CB.17Sc.IgG-Foxn1Nj) were obtained from The Jackson Laboratory and housed under sterile conditions in barrier cages. Each of 19 mice was implanted with 5 × 10⁶ freshly harvested (97% viable) MDA-MB-231 cells in Matrigel (Sigma-Aldrich). Mice received an i.p. injection of either 100 μg of 3.2G1 or isotype control Ab weekly for the following 3 wk (total injections = 4). Animals were held for at least 1 wk after the appearance of the last tumor in the isotype control group (a total of 70 days) before totaling frequency of occurrence. All tumors reached ≥3 mm in diameter before being scored as positive.

Statistics

The significance value for the tumor implantation studies was calculated using the Fisher exact test in the program Sigma Stat (SPSS).

Results

Generation of TCRm Abs specific for the HLA-A2-GVL peptide complex

BALB/c mice were immunized and boosted with HLA-A2 complexes prepared by refolding E. coli-expressed HLA-A2 and β₂m in the presence of the hCGβ peptide located at 47–55 aa (designated GVL). Following the second boost, mice were sacrificed and splenocytes were isolated and used in a standard hybridoma fusion protocol. After growth in semisolid medium, clones were transduced with nonpulsed cells were used as negative controls. After pulsing and the addition of Ab, cells were stained and analyzed. The MFI of cells stained with the 3.2G1 Ab titrated over a range from 10 to 150 MFI, whereas the IgG1 isotype does not (27). This fact and the corresponding ability of this isotype to bind human FcR (see below) led to our selection of the 3.2G1 TCRm Ab. T2 cells pulsed with various peptides were used as targets for the initial 3.2G1-directed CDC analysis, because they could easily be loaded to a high density with any of a number of peptides. The effect of the relative
density of the appropriate peptide-A2 complex on the surface of T2 cells was probed by pulsing with GVL, TMT, a mixture of the two, or no peptide while holding the Ab concentration constant at 2.5 μg/ml. Fig. 2A illustrates the CDC results of cells pulsed with various ratios of peptide (GVC to TMT) for both the HLA-A2-specific BB7.2 Ab and 3.2G1. BB7.2 is a murine IgG2b Ab and this isotype also efficiently fixes complement (27). BB7.2-driven lysis demonstrates that there is little difference between cells pulsed with peptides at the various concentrations. The lysis of nonpulsed cells is lower, as might be expected, because staining studies with these cells indicate that they display a lower but substantial level of HLA-A2 on their surface (data not shown). The addition of 3.2G1 Ab to the cells resulted in CDC that titrated with the ratio of GVL to TMT. Lysis was not seen for nonpulsed cells (the value was below the spontaneous release in the absence of Ab) or those pulsed with TMT (CDC < 2%). This experiment implies that the degree of lysis reflects the Ag density on the cell.

In a second experiment, an examination of the relationship between target density and cell lysis was conducted using T2 cells that were pulsed by pulsing with GVL, TMT, a mixture of the two, or no peptide while holding the Ab concentration constant at 2.5 μg/ml. Fig. 2A illustrates the CDC results of cells pulsed with various ratios of peptide (GVC to TMT) for both the HLA-A2-specific BB7.2 Ab and 3.2G1. BB7.2 is a murine IgG2b Ab and this isotype also efficiently fixes complement (27). BB7.2-driven lysis demonstrates that there is little difference between cells pulsed with peptides at the various concentrations. The lysis of nonpulsed cells is lower, as might be expected, because staining studies with these cells indicate that they display a lower but substantial level of HLA-A2 on their surface (data not shown). The addition of 3.2G1 Ab to the cells resulted in CDC that titrated with the ratio of GVL to TMT. Lysis was not seen for nonpulsed cells (the value was below the spontaneous release in the absence of Ab) or those pulsed with TMT (CDC = 2%). This experiment implies that the degree of lysis reflects the Ag density on the cell.

In a second experiment, an examination of the relationship between target density and cell lysis was conducted using T2 cells that were pulsed with varying levels of GVL peptide alone (Fig. 2B). The peptide was serially diluted and added to cells at concentrations ranging from 100 to 0.1 μg/ml. VLQ peptide and nonpulsed cells were used as a zero-point control. After pulsing and addition of Ab at 10 μg/ml, cells were subjected to CDC analysis. The HLA-A2-specific lysis in the presence of BB7.2 varied from 55 to 85%, whereas that driven by 3.2G1 varied from 10 to 60% (Fig. 2B), titrating with the dose of peptide used to pulse cells. Although there was no indication of a significant decrease in cell lysis for BB7.2, there was a clear relationship between target density and cell lysis demonstrated by 3.2G1, with half-maximal lysis occurring at a peptide concentration of around 6 μg/ml.

In the final CDC experiment involving T2 cells, we further examined the specificity of lysis by the Ab using HLA-A2-peptide tetramers to compete for 3.2G1 binding. 3.2G1 TCRm was serially diluted and preincubated with tetramer such that the final concentrations of TCRm varied from 9 to 0.1 μg/ml and the tetramer concentration was 2 μg/ml after addition to the CDC reaction. Tetramers refolded with the GVL peptide (competitor) substantially inhibited CDC, whereas those refolded in the presence of VLQ peptide (noncompetitor) resulted in an Ab lysis profile almost identical with that seen with no tetramer (Fig. 2C). Taken together, these findings support the fine recognition specificity of the 3.2G1 TCRm mAb for targeting the GVL-A2 epitope on T2 cells for cell lysis by CDC.

3.2G1 detects endogenous GVL peptide-HLA-A2 presented on human tumor cell lines

The ability of the 3.2G1 Ab to detect endogenously processed peptide in the context of the HLA-A2 molecule was evaluated by immunofluorescent staining of a series of tumor cell lines (Fig. 3).
BB7.2 mAb indicated the level of HLA-A2 expression on cells. SKOV3.A2 and SW620 are ovarian and colon cancer cell lines, respectively, whereas MDA-MB-231 and BT20 are breast cancer cell lines. Additional analysis of the SKOV3.A2, SW620, and MDA-MB-231 cell lines by ELISA indicated that hCG was present in these lines (data not shown). BT20 cells were not evaluated for the presence of hCG but were included as an HLA-A2-negative control. The three HLA-A2-positive tumor cell lines displayed different levels of GVL/A2 when stained with the 3.2G1 TCRm, and as might be anticipated, the staining intensity varied in accordance with the level of HLA-A2 on the surface. The HLA-A2-negative cell line, BT-20, was not stained with either 3.2G1 or BB7.2. Because of its consistently high level of expression of GVL/A2 and to maximize the target density, we selected the MDA-MB-231 cell line as the target for the following in vitro and in vivo assays.

**FIGURE 2.** CDC of peptide-pulsed T2 cells. T2 cells were pulsed with the various peptide mixes for 4 h, washed, and dispensed into wells in 96-well plates at $3 \times 10^5$ cells per well. Ab and rabbit complement were added, and the reactions were allowed to proceed for 4 h, and then cytotoxicity was analyzed using the LDH assay from Promega. A, T2 cells were pulsed with mixes of GVL:TMT peptide at the concentrations in μg/ml shown in the legend for 4 h before incubating with 2.5 μg/ml 3.2G1 TCRm or BB7.2 Ab and rabbit complement. B, T2 cells were pulsed with varying levels of peptide diluted 1:2 from 50 to 0.1 μg/ml before incubating with 10 μg/ml 3.2G1 TCRm or BB7.2 Ab. C, T2 cells were pulsed with 20 μg/ml peptide before addition of a mix containing varying amounts of Ab and either GVL or VLQ tetramer at a final concentration of 2 μg/ml tetramer. Final Ab concentration (μg/ml): 9 (light gray), 3 (dark gray), 1 (black), 0.3 (right hatch), 0.1 (left hatch).

BB7.2 mAb indicated the level of HLA-A2 expression on cells. SKOV3.A2 and SW620 are ovarian and colon cancer cell lines, respectively, whereas MDA-MB-231 and BT20 are breast cancer cell lines. Additional analysis of the SKOV3.A2, SW620, and MDA-MB-231 cell lines by ELISA indicated that hCGβ was present in these lines (data not shown). BT20 cells were not evaluated for the presence of hCGβ but were included as an HLA-A2-negative control. The three HLA-A2-positive tumor cell lines displayed different levels of GVL/A2 when stained with the 3.2G1 TCRm, and as might be anticipated, the staining intensity varied in accordance with the level of HLA-A2 on the surface. The HLA-A2-negative cell line, BT-20, was not stained with either 3.2G1 or BB7.2. Because of its consistently high level of expression of GVL/A2 and to maximize the target density, we selected the MDA-MB-231 cell line as the target for the following in vitro and in vivo assays.

The 3.2G1 TCRm mAb directs killing of a human tumor cell line in vitro

The breast cancer cell line MDA-MB-231 was subjected to competition analysis via tetramer blockade of CDC in the same manner in which the T2 cells were evaluated (described above). Cells were plated and allowed to adhere overnight before Ab or Ab plus tetramer was applied. Ab concentration was varied from 25 to 1 μg/ml and tetramer concentration was held constant at 6 μg/ml. CDC of cells incubated with Ab in the absence of tetramer showed an Ab concentration-dependent lysis which was paralleled by cells incubated with Ab in the presence of VLQ tetramer. This indicated that there was essentially no competition provided by the tetramer (Fig. 4A). In contrast, cells incubated in the presence of Ab plus GVL tetramer were almost completely protected from lysis even at the highest concentration of Ab used. These findings further demonstrate the specificity of the 3.2G1 TCRm and indicate that use of this class of Ab as a full-length molecule offers a novel approach for targeting and killing tumor cells.

A second mechanism that plays an important role in the ability of a therapeutic Ab to control or eliminate tumors is ADCC (12, 13, 15). To investigate the ability of the 3.2G1 TCRm mAb to direct ADCC, we isolated PBMC from the platelet chambers of apheresis collection devices from anonymous donors. The cells were held in serum-free medium (AIM-V) containing 200 U/ml recombinant human IL-2 for 2–7 days, with medium changes every 2–3 days to maintain and activate the NK population (25). To determine the level of NK activity present in the different donor samples, each preparation was evaluated using the NK-sensitive cell line K562 at the same time the ADCC assays were conducted. All PBMC isolates were shown to exhibit lysis levels ≥60%, with one exception (35%) (data not shown).

MDA-MB-231 cells were first evaluated for sensitivity to ADCC as adherent cultures using five different human PBMC preparations to control for variation among the individual donors. Fig. 4B shows the results of these assays, which contained 10 μg/ml 3.2G1 TCRm and were run at an E:T ratio of 30:1. The PBMC preparations varied in their ability to lyse MDA cells as might be anticipated due to differences in receptor expression by NK cells. The overall ADCC ranged from 6.8 to 9.6%, with an average value of 8.7%.
isotype-treated group had developed tumors that were the last tumor in the control mice. At day 69, 8 of 10 mice in the scoring was tabulated on day 69, 21 days after the appearance of volume and expand in the control mice until day 49 (week 6 tumor any of the mice treated with 3.2G1. Tumors continued to appear 43 days (week 6) after implantation, while none were evident in in vivo
To establish the ability of the 3.2G1 TCRm to inhibit tumor growth in vivo, we implanted nude mice with MDA-MB-231 tumor cells. Ab treatment was initiated at the time of implantation with an i.p. injection of either 3.2G1 TCRm or an isotype control Ab. Tumors began to appear in the isotype control-treated mice between 36 and 43 days (week 6) after implantation, while none were evident in any of the mice treated with 3.2G1. Tumors continued to appear and expand in the control mice until day 49 (week 6 tumor volume = 4.5 mm³; week 10 tumor volume = 157 mm³). Final scoring was tabulated on day 69, 21 days after the appearance of the last tumor in the control mice. At day 69, 8 of 10 mice in the isotype-treated group had developed tumors that were ≥6 mm in diameter, while none of the nine mice in the group treated with the 3.2G1 TCRm showed evidence of tumor growth (Fig. 5). The experiment was terminated at 71 days.

Discussion

The current study characterizes the functional properties of an Ab with the type of HLA-restricted peptide specificity associated with TCR. The similarity in epitope recognition to a TCR has led us to designate this Ab a TCRm and to investigate its potential as a therapeutic agent. The 3.2G1 TCRm is a murine IgG2a mAb that 1) can mediate the staining and lysis of cells bearing the GVL peptide-HLA complex on their surface by both CDC and ADCC and 2) is capable of protecting mice from growth of an implanted human breast cancer cell line. 3.2G1 TCRm immunofluorescent staining intensity was proportional to the Ab concentration and to the amount of peptide present on the surface of the T2 cell. Staining also was blocked in a dose-dependent manner by GVL/A2 tetramers added to the staining buffer. Titration of the peptide used to pulse T2 cells resulted in demonstration of a direct correlation between the staining intensity and the extent of specific cell lysis by CDC.

The potential for therapeutic application of TCR mimic Abs was realized early in their development (32–34). There have been a number of Abs developed that target tumor epitopes, and the majority of these were produced as Fab on bacteriophage. The therapeutic utility of the bacteriophage-derived Fab Abs have been investigated by creating genetic constructs in which the Ab’s recognition domain is used to specifically target cells expressing the peptide-HLA complex. Targeting of influenza-infected cells or melanoma cell lines with anti-peptide-MHC Fab-immunotoxin conjugates has been shown to inhibit cell growth in vitro (35, 36). One of the limitations of using phage display is that the random association of L and H chain fragments may not generate binding pairs of the highest affinity. For example, Chames et al. (37) subjected a phage-derived Fab to mutagenesis to develop a 2-log increase in staining sensitivity and more efficient tumor killing by the MAGE/A1-specific TCRm. The advantages of developing TCR mimic IgG mAbs include the acquisition of matched heavy and L chain pairs that have been affinity matured in the animal and the ability to activate immune effector functions via the Fc domain of the molecule without further genetic modification. In vitro and in vivo characterization of full-length Ab-like molecules that recognize an MHC-restricted peptide are rare. Aharoni et al. (34) reported the use of an Ab, made by the hybridoma fusion technique, to a murine MHC-II molecule loaded with a basic protein from rat in a CDC assay format. Mosquera et al. (38) have reported the in vitro and in vivo characterization of a TCR-human IgG chimeric fusion protein that is specific for the p53 peptide (264–272). In this report, we showed the efficacy of the 3.2G1 TCRm as a therapeutic agent by examining its ability to trigger CDC and ADCC of a tumor line in vitro and prevent tumor growth in vivo. To our knowledge, this is the first demonstration of use of a “naked” TCRm mAb as a therapeutic agent.

Elimination of tumors in vivo by Ab therapy is thought to be the result of any or all of a number of mechanisms including blockade of growth factor receptors, induction of apoptosis, CDC and ADCC. The efficacy of growth factor receptor blockade has been shown in tumor xenotransplantation experiments with murine
anti-EGF and anti-neu Abs which significantly inhibit tumor growth in mice (16, 39). These effects appeared to be independent of Ab isotype because IgG1, IgG2a, and IgG2b suppress growth, whereas only the IgG2a and 2b isotypes show any in vitro activity in CDC and ADCC experiments. In contrast with Abs that bind and block growth factor receptors, studies using Abs that are directed at other targets, such as Abs that recognize surface IgM or Thy 1.1 on murine lymphomas, show a direct correlation between in vitro activity and tumor regression (40, 41). Studies by Clynes et al. (42) using FcγR/H9253R-chain knockout mice demonstrated that the efficacy of anti-HER2 and anti-CD20 Abs (trastuzumab and its murine Ab predecessors and rituximab) is significantly reduced in the absence of functional receptors. In addition, they demonstrated that inactivation of the inhibitory FcγR/H9253RII increased ADCC, indicating that FcR-mediated events play an important role in tumor suppression (15). Mice deficient in the initiating factor for the classical complement pathway, C1q, were used to show that this pathway is essential for the therapeutic activity of rituximab (43).

Comparison of the results of CDC analysis of peptide-pulsed T2 cells and the MDA-MB-231 tumor line appeared to demonstrate that a higher Ab concentration was necessary to achieve lysis and that overall lysis was lower for the MDA-MB-231 tumor line. A number of known inhibitors of the complement system exist, including CD46, CD55, and CD59 (membrane cofactor of proteolysis, decay-accelerating factor, and protection or Mac inhibitor, respectively). Although the exact effect of these inhibitors on the complement components present in the rabbit serum used in these studies is disputed, it follows that their presence may reduce or inhibit lysis (44–47). MDA-MB-231 cells have been reported to express moderate levels of CD46 and high levels of CD55 and CD59 when evaluated by flow cytometry (13). Samples from patients with multiple myeloma and non-Hodgkins lymphoma (NHL), as well as NHL cell lines that were resistant to CDC, tested positive for these markers (23, 48). Blockade of the inhibitors enhanced lysis in all cases with CD59 neutralization having the most dramatic effect (23). Thus, it appears that reduced lysis of the MDA cells in our experiments could be linked to the presence of specific inhibitors of CDC expressed by this line.

FIGURE 4. CDC and ADCC of MDA-MB-231 cells by 3.2G1 TCRm. A, CD cytolysis was conducted using 2 × 10⁵ MDA-MB-231 cells well in a 96-well plate. The final concentrations of the Abs in the wells were (µg/ml): 25 (light gray), 10 (dark gray), 5 (black), 2.5 (right hatch), and 1 (left hatch). Tetramer concentration in each well was 6 µg/ml. Reactions were incubated for 4 h and analyzed using the LDH assay. B, ADCC reactions included 2 × 10⁵ MDA-MB-231 cells per well and IL-2-stimulated human PBMC preparations at an E:T ratio of 30:1 with 10 µg/ml 3.2G1. Lysis was determined using the LDH assay. C, ADCC reactions using IL-2-stimulated human PBMC at an E:T ratio of 20:1 with either 10 µg/ml 3.2G1 or 10 µg/ml W6/32. Bars indicate SE for each reaction. Data from CDC assays are representative of four independent experiments.
The ADCC assays presented indicated that the two murine Abs that recognize human HLA, 3.2G1, and W6/32, were at best moderately efficient at directing lysis by NK cells. These results do not differ significantly from those reported for rituximab by Harjunpaa et al. (23) or Golay et al. (24), in which various NHL cell lines were tested and the level of cytotoxicity was reported to be between 8 and 25% specific lysis. Harjunpaa et al. (23) categorized this level of lysis as relatively ineffective, whereas Golay et al. (24) reported values between 2.5 and 30-fold (○). In contrast, no tumor growth was seen in mice treated with the 3.2G1 Ab (■). Tumors were monitored, and final scoring was tabulated at 69 days after implant, at which time all tumors were ≥6 mm in diameter and no new tumors had appeared for 21 days. Tumor volumes were calculated by assuming a spherical shape and using the following formula: volume = 4π/3, where r = 1/2 of the mean tumor diameter measured in two dimensions. Points, median; bars, SEM. Significance p = 0.0007 was determined by the Fisher exact test.

FIGURE 5. The 3.2GITCRm prevents tumor growth in athymic nude mice. Female athymic mice were subcutaneously injected between the shoulders with 5 × 106 MDA-MB-231 cells in 0.2 ml containing a 1:1 mixture of medium and Matrigel. Mice were given tumor cells and treated i.p. with 100 μg of either murine IgG2a isotype control Ab or with GVL/A2-specific 3.2G1 TCRm Ab. After the initial Ab injection, mice received one injection per week (50 μg per injection) for 3 wk. Tumor growth was initially seen in mice treated with IgG2a control Ab at wk 6, and by wk 10, the tumor volume had increased >30-fold (○). In contrast, no tumor growth was seen in mice treated with the 3.2G1 Ab (■). Tumors were monitored, and final scoring was tabulated at 69 days after implant, at which time all tumors were ≥6 mm in diameter and no new tumors had appeared for 21 days. Tumor volumes were calculated by assuming a spherical shape and using the following formula: volume = 4π/3, where r = 1/2 of the mean tumor diameter measured in two dimensions. Points, median; bars, SEM. Significance p = 0.0007 was determined by the Fisher exact test.


