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(54) **METHOD FOR PREPARATION OF SINGLE CHAIN ANTIBODIES**

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(57) **ABSTRACT**

This invention provides a method for identifying cells expressing a target single chain antibody (scFv) directed against a target antigen from a collection of cells that includes cells that do not express the target scFv, comprising the step of combining the collection of cells with an anti-idiotype directed to an antibody specific for the target antigen and detecting interaction, if any, of the anti-idiotype with the cells, wherein the occurrence of an interaction identifies the cell as one which expresses the target scFv. This invention also provides a method for making a single chain antibody (scFv) directed against an antigen, wherein the selection of clones is made based upon interaction of those clones with an appropriate anti-idiotype, and heretofore inaccessible scFv so made. This invention provides the above methods or any combination thereof. Finally, this invention provides various uses of these methods.

7 Claims, 16 Drawing Sheets

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U.S. Office Action, Mar. 20, 2008, for Nai-Kong V. Cheung, U.S. Appl. No. 10/505,658, filed Aug. 20, 2004.

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FIGURE 1

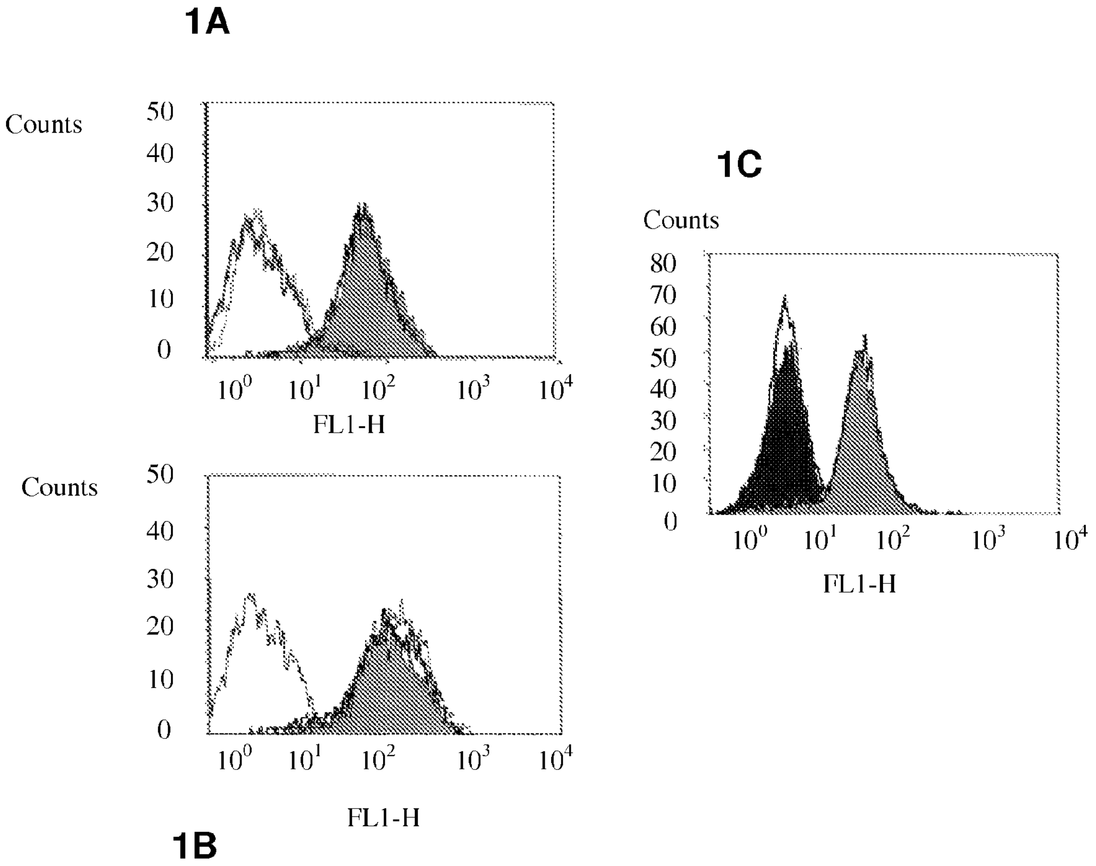

1A
Counts
50
40
30
20
10
0
10^0
10^1
10^2
10^3
10^4
FL1-H
Counts
50
40
30
20
10
0
10^0
10^1
10^2
10^3
10^4
FL1-H
1B
1C
Counts
80
70
60
50
40
30
20
10
0
10^0
10^1
10^2
10^3
10^4
FL1-H

FIGURE 2

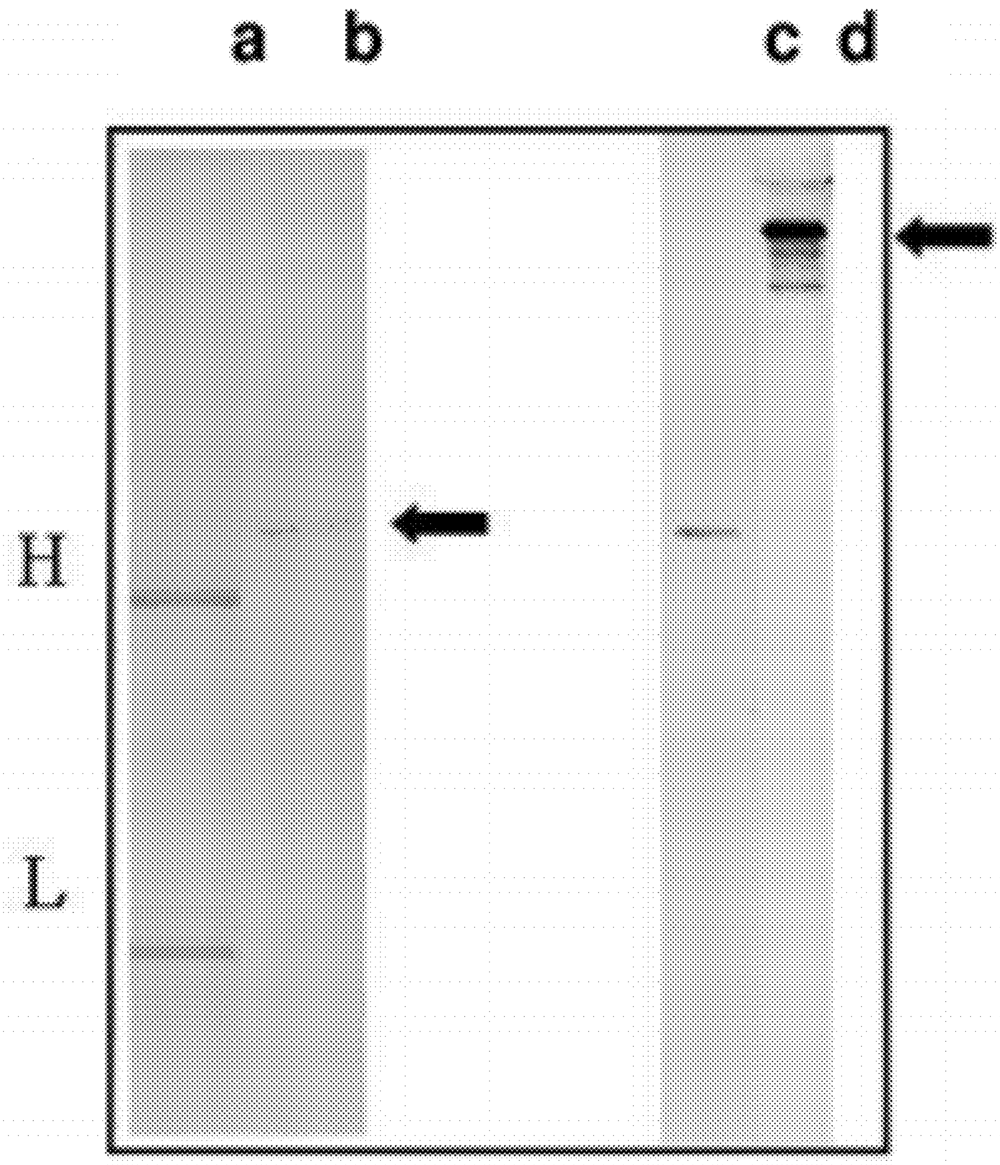


FIGURE 3

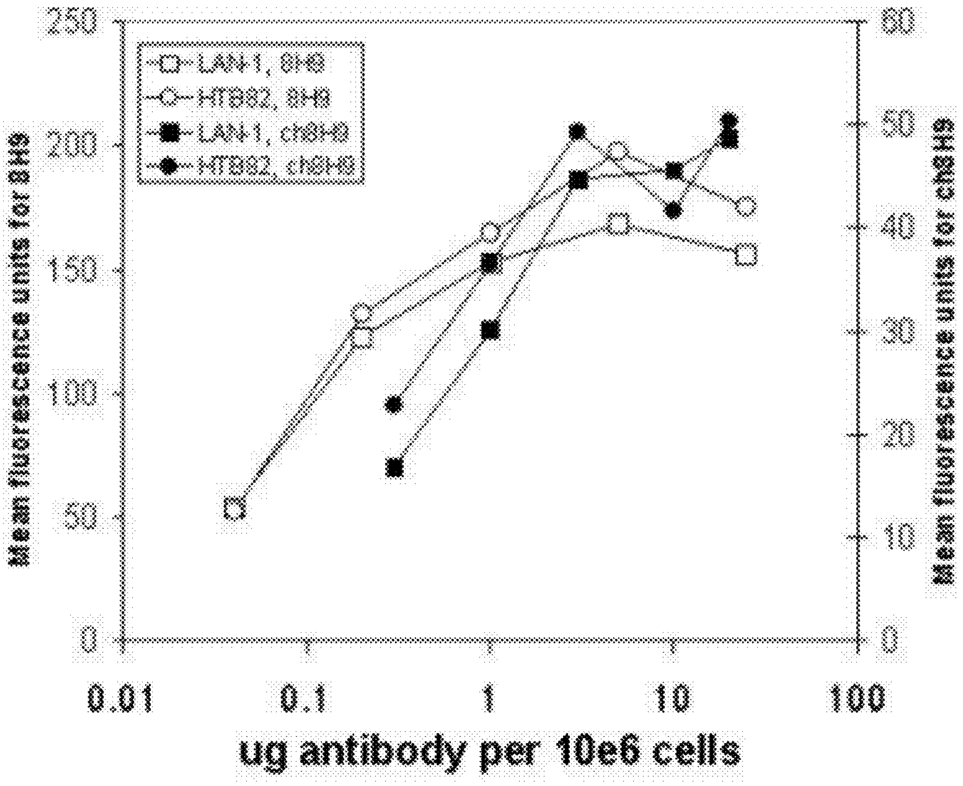

LAN-1, 8H9
HTB82, 8H9
LAN-1, ch8H9
HTB82, ch8H9
Mean fluorescence units for 8H9
0
50
100
150
200
250
Mean fluorescence units for ch8H9
0
10
20
30
40
50
60
0.01
0.1
1
10
100
ug antibody per 10e6 cells

FIGURE 4

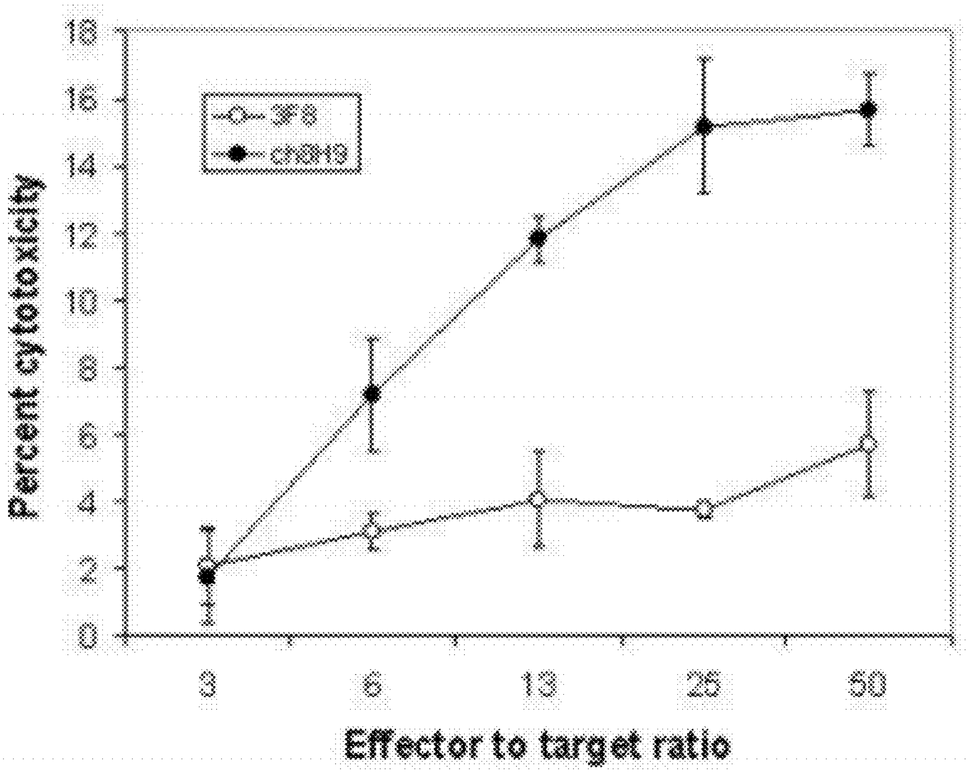

3F8
ch8H9
Percent cytotoxicity
0
2
4
6
8
10
12
14
16
18
3
6
13
25
50
Effector to target ratio

FIGURE 5

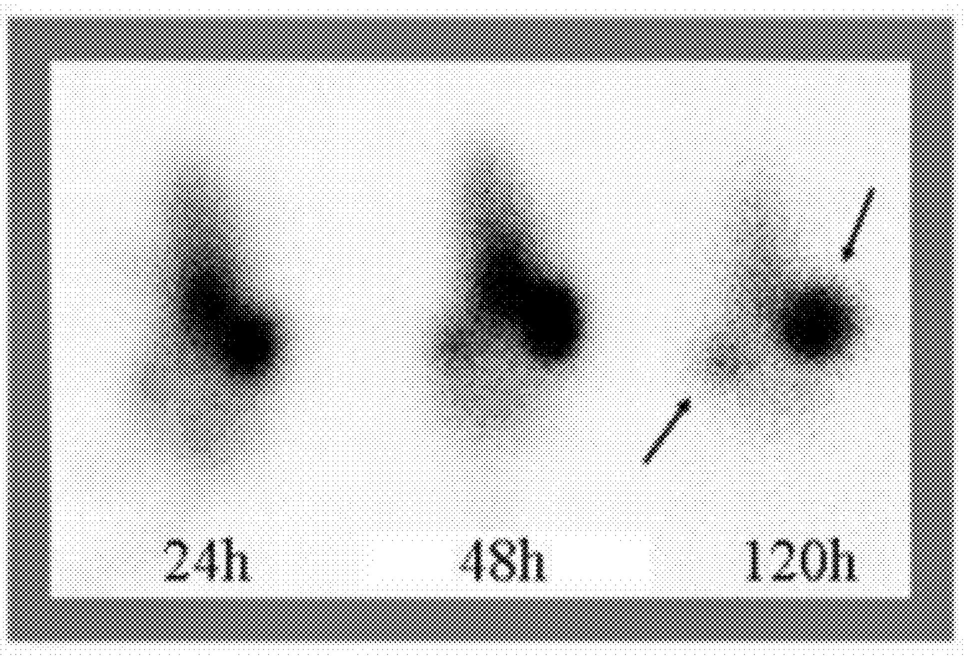


FIGURE 6

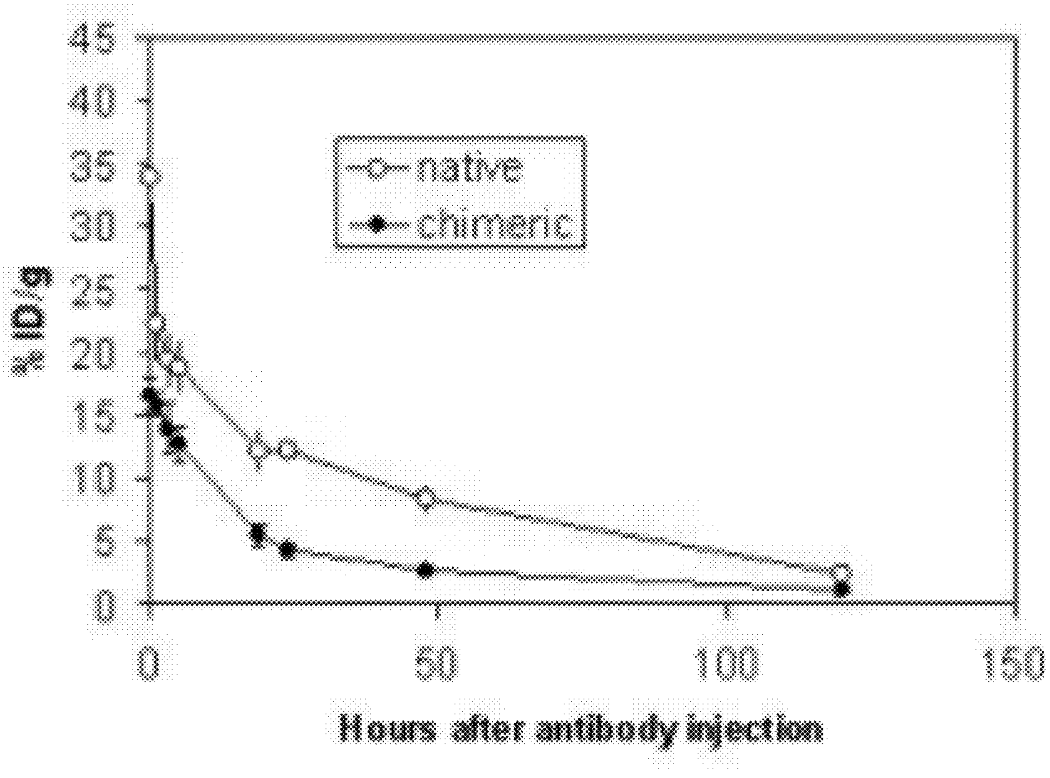

45
40
35
30
25
20
15
10
5
0
% ID/g
native
chimeric
0
50
100
150
Hours after antibody injection

FIGURE 7

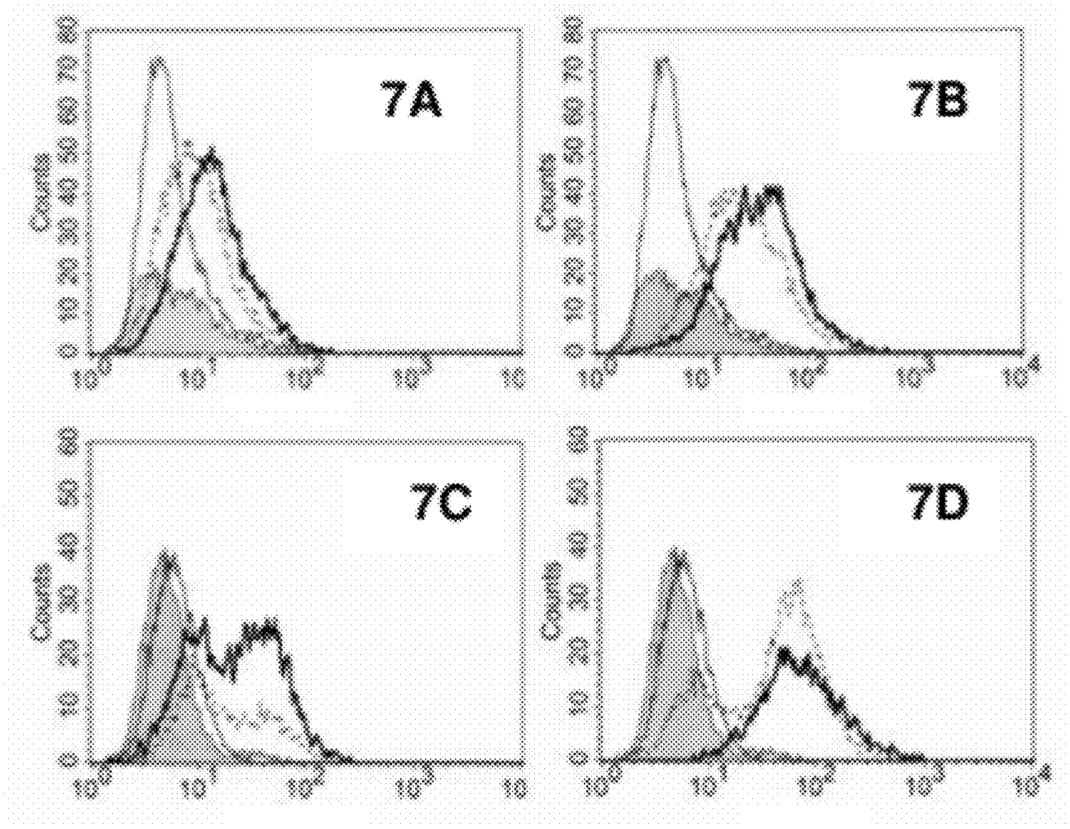


FIGURE 8

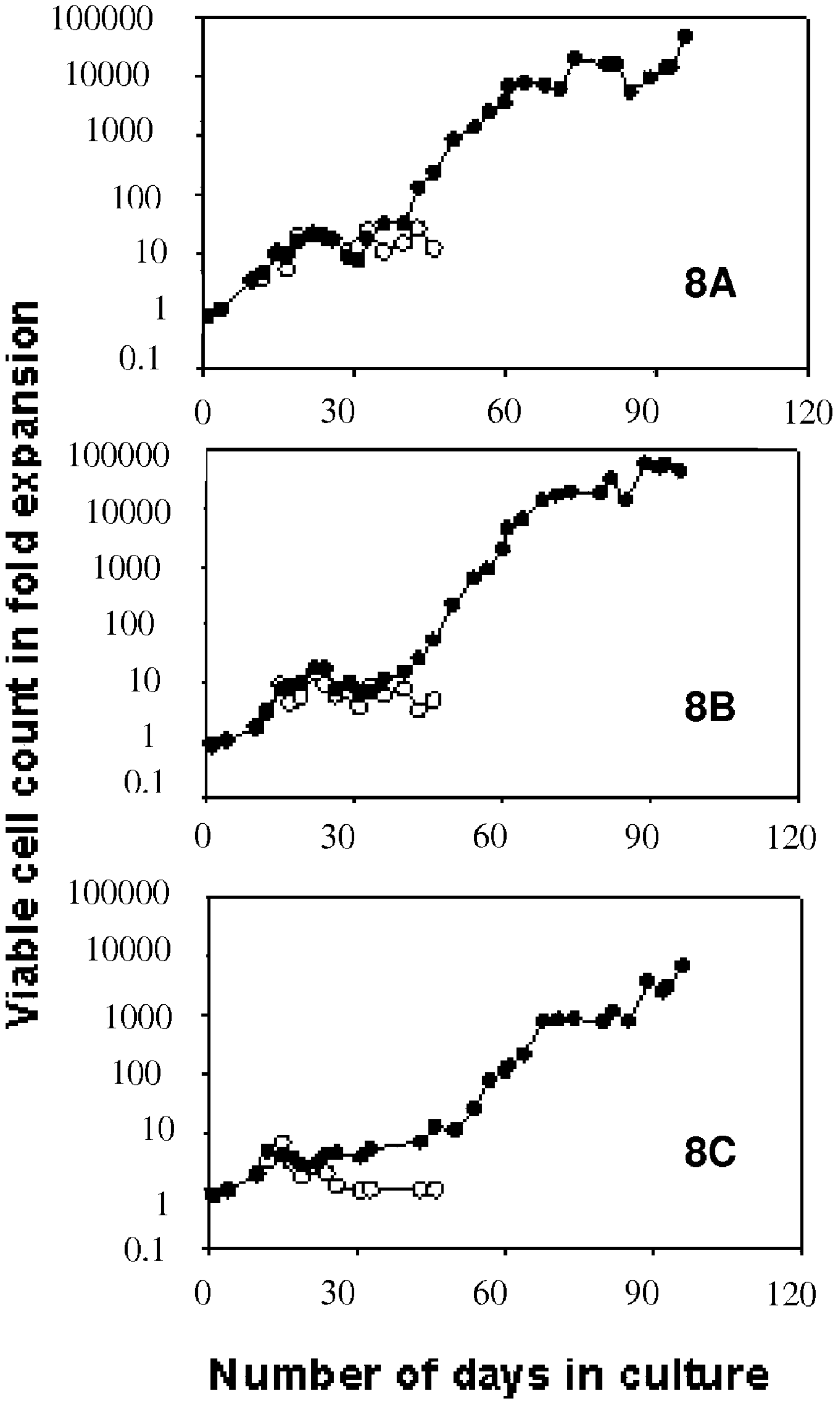

100000
10000
1000
100
10
1
0.1
0
30
60
90
120
8A
100000
10000
1000
100
10
1
0.1
0
30
60
90
120
8B
100000
10000
1000
100
10
1
0.1
0
30
60
90
120
8C
Viable cell count in fold expansion
Number of days in culture

FIGURE 9

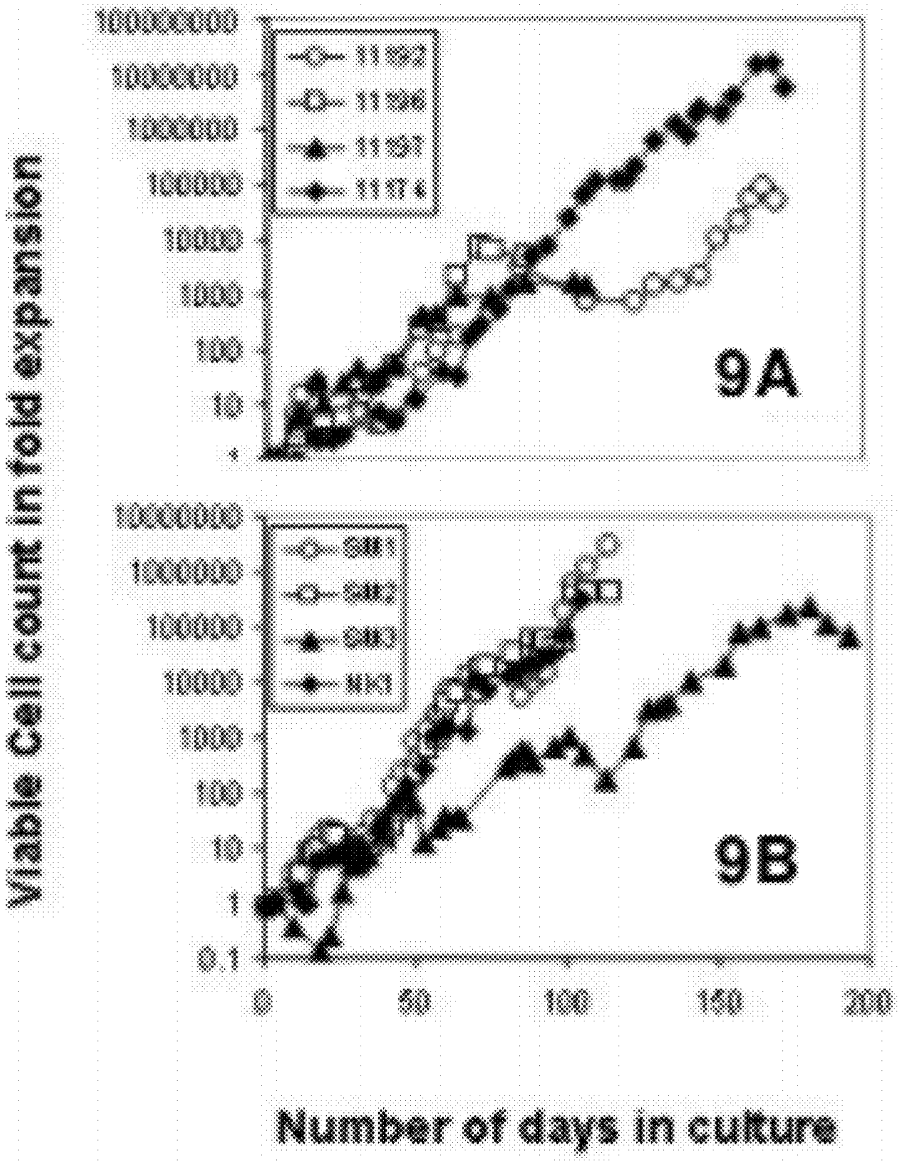

Viable Cell count in fold expansion
100000000
10000000
1000000
100000
10000
1000
100
10
1
11192
11196
11197
11174
9A
1000000
100000
10000
1000
100
10
1
0.1
SH1
SH2
SH3
NK1
9B
0
50
100
150
200
Number of days in culture

FIGURE 10

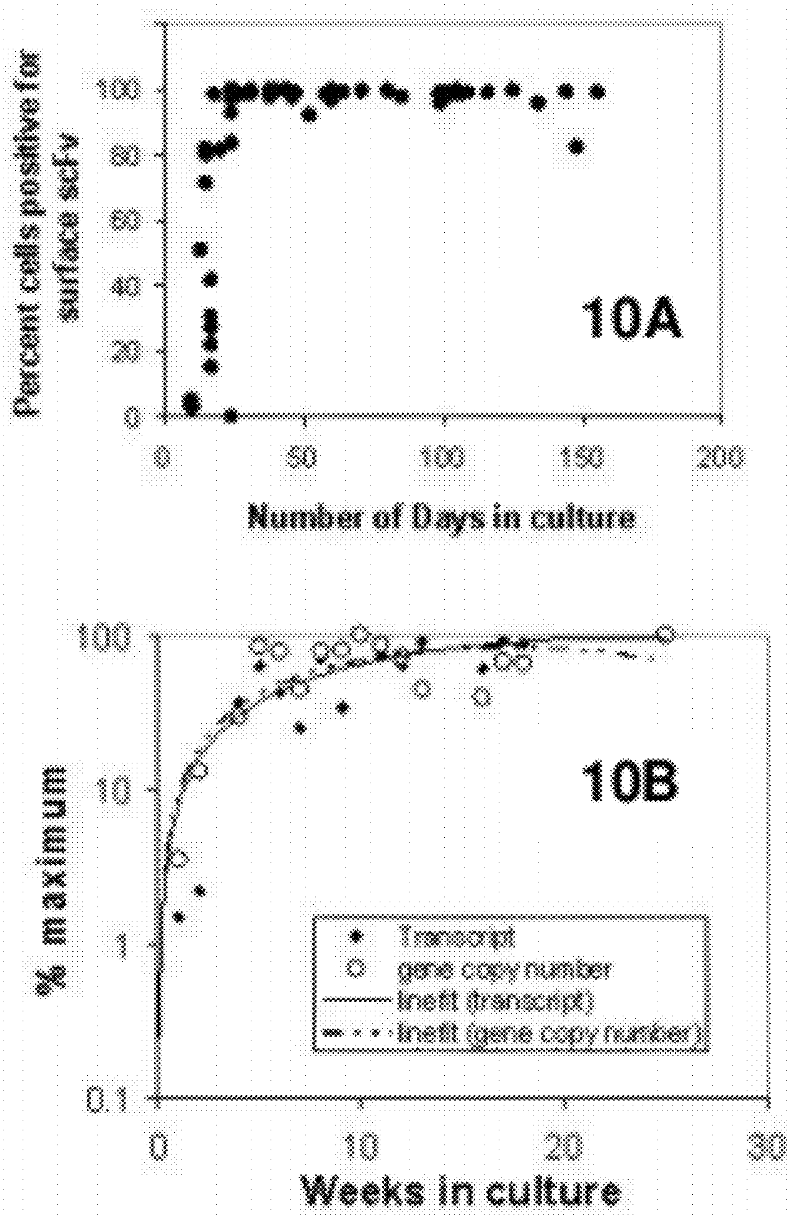

Percent cells positive for surface scFv
100
80
60
40
20
0
0
50
100
150
200
Number of Days in culture
10A
% maximum
100
10
1
0.1
0
10
20
30
Weeks in culture
10B
Transcript
gene copy number
linefit (transcript)
linefit (gene copy number)

FIGURE 11

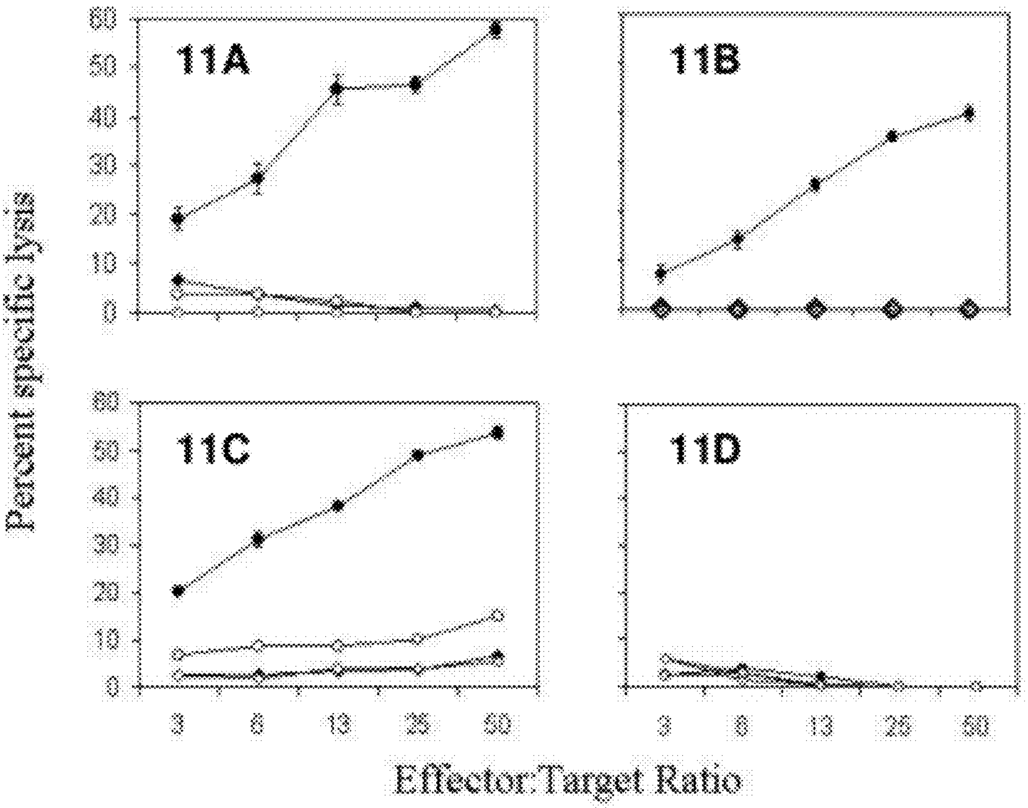

11A
11B
11C
11D
Percent specific lysis
0
10
20
30
40
50
60
3
6
13
25
50
Effector:Target Ratio

FIGURE 12

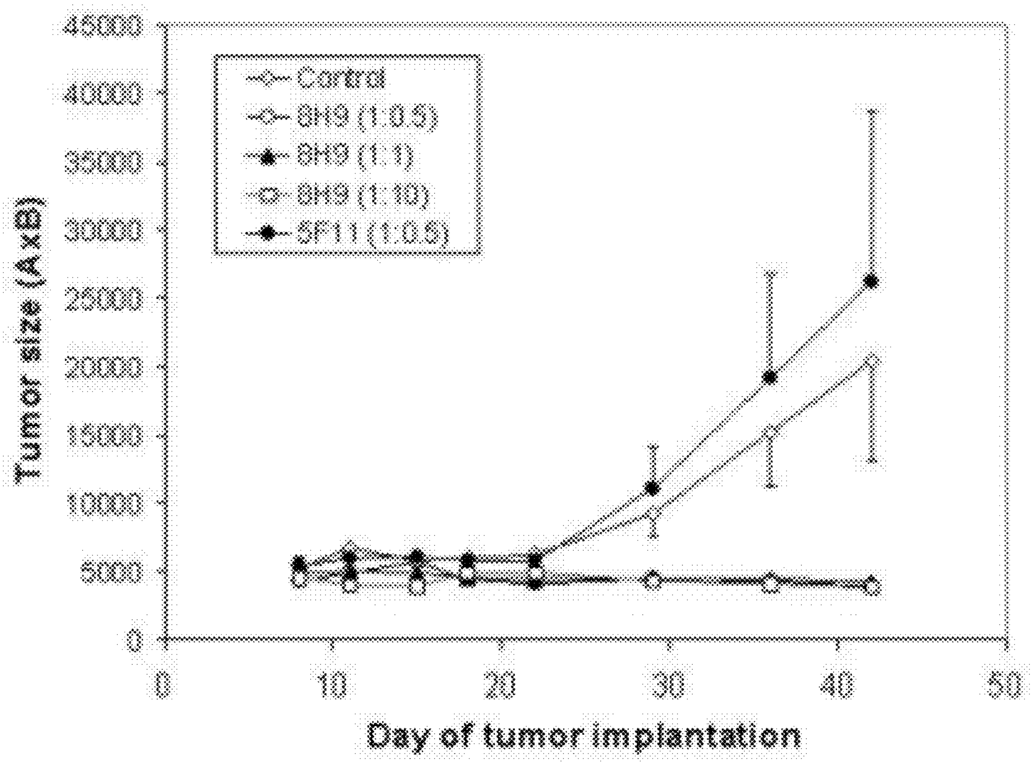

Control
8H9 (1:0.5)
8H9 (1:1)
8H9 (1:10)
5F11 (1:0.5)
Tumor size (AxB)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
Day of tumor implantation

FIGURE 13

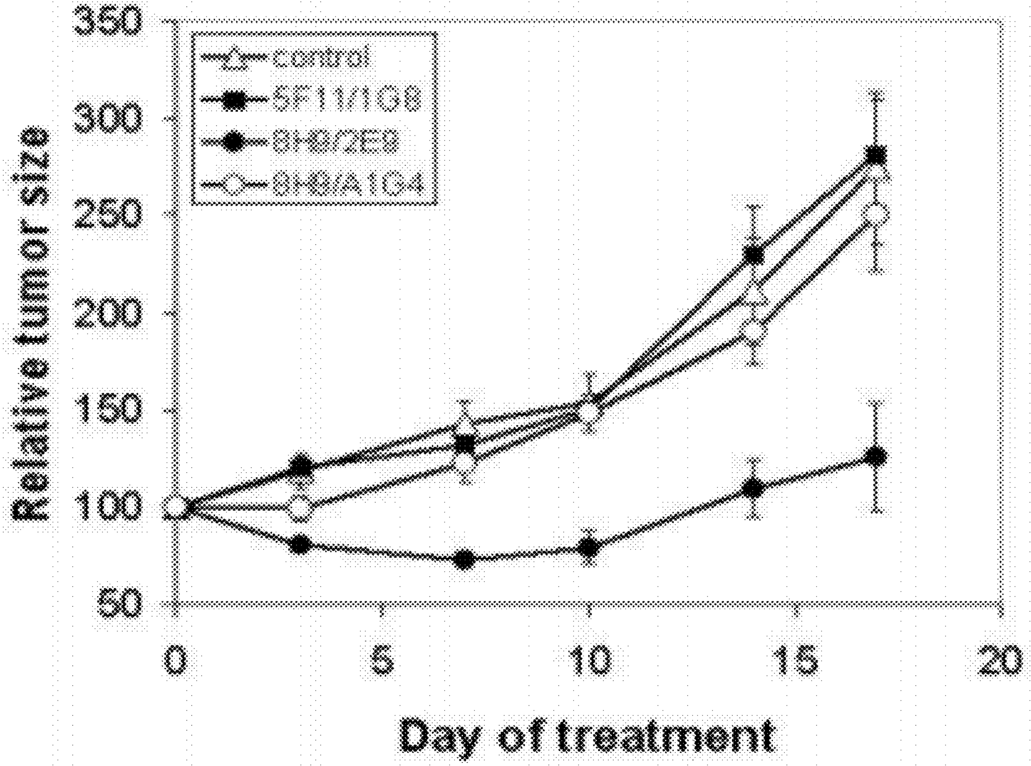
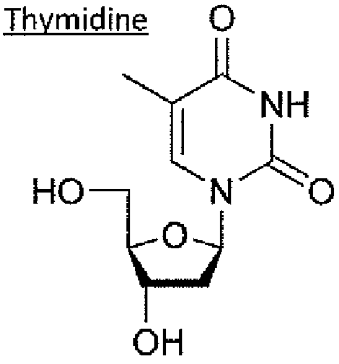

control
5F11/1G8
8H9/2E9
8H9/A1G4
Relative tumor size
350
300
250
200
150
100
50
0
5
10
15
20
Day of treatment

FIGURE 14

Thymidine



FIAU

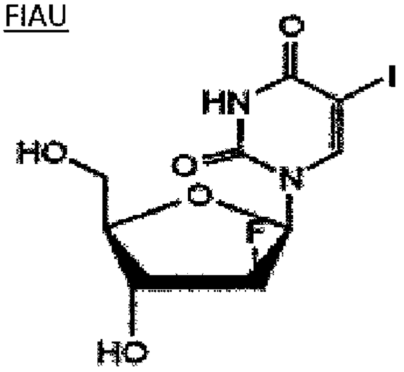


FIGURE 15

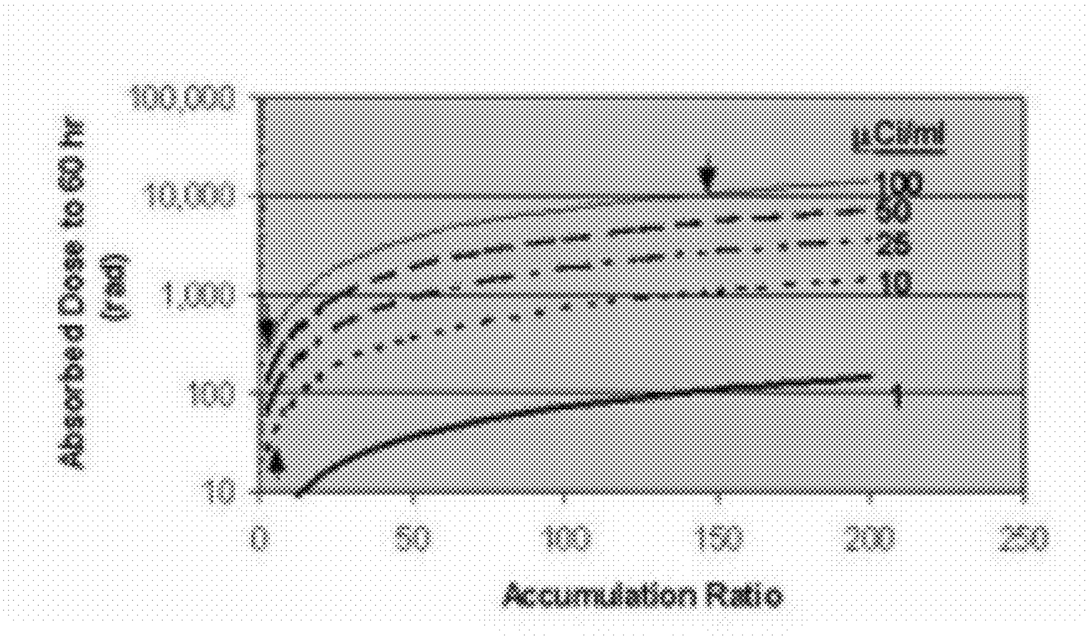
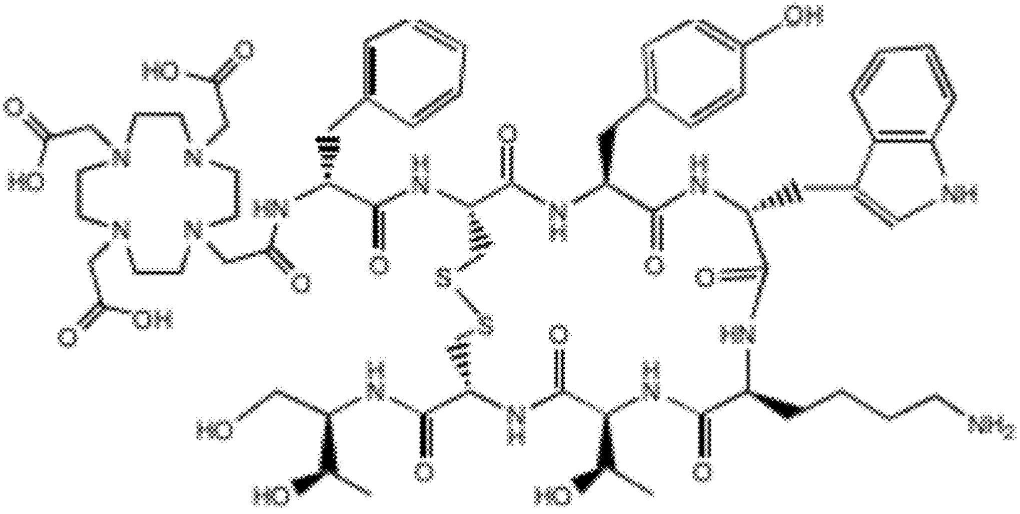

Absorbed Dose to 60 hr (rad)
100,000
10,000
1,000
100
10
µCi/ml
100
50
25
10
1
0
50
100
150
200
250
Accumulation Ratio

FIGURE 16


HO
O
OH
HO
O
N
N
N
N
O
O
OH
HN
H
N
O
O
S
S
O
N
H
O
OH
H
N
O
O
NH
O
HN
NH
H
N
O
N
H
O
H
N
O
NH2
HO
HO
HO

METHOD FOR PREPARATION OF SINGLE CHAIN ANTIBODIES

This application is a Divisional Application of U.S. Ser. No. 10/273,762, filed Oct. 17, 2002, which claims priority of U.S. Ser. No. 60/330,396, filed 17 Oct. 2001; Int'l App'l No. PCT/US01/32565, Filed 18 Oct. 2001; and U.S. Ser. No. 10/097,558, Filed 8 Mar. 2002, the content of which is incorporated by reference here into this application.

This application was supported in part by Department Of Energy Grant No. DE-FG-02-93ER61658, National Institute of Health Grant No. CA61017 and National Cancer Institute Grant No. NCICA 89936. Accordingly, the United States Government may have certain rights in this invention.

Throughout this invention, various references are referred to. Disclosures of these publications in their entireties are hereby incorporated by reference into this application to more fully describe the state of the art to which this invention pertains.

BACKGROUND OF THE INVENTION

This invention relates to a method for preparation of single chain antibodies, and is of particular applicability to preparation of single chain Fv antibody fragments (scFv) where the antigen to which the antibody binds is difficult to purify.

ScFv are antibody constructs comprising the variable regions of the heavy and light chains of an antibody as a single chain Fv fragment. ScFv technology utilizes molecular biology methods to reduce antibodies to the minimal-required-unit of heavy and light chain variable regions tethered by a peptide linker which can be designed with versatile side chains for radioconjugation.

Procedures for making scFv are known in the art. These procedures generally involve amplification of gene regions encoding the variable regions of the antibodies, assembly of an scFv genetic sequence and expression of the scFv genetic sequence in host cells. The host cells are screened using a target antigen to identify those cells which bind to the antigen, ands thus which express a functional scFv of the desired specificity. While this procedure works well in many cases, it requires the isolation of the antigen for use as a screening tool. In some cases, however, particularly in the case of membrane bound receptor molecules, this isolation may be difficult, or the conformation of the isolated antigen may be so different that it fails to present the same epitopes for binding. In these cases, the conventional techniques for development of an scFv are either unworkable or very difficult.

SUMMARY OF THE INVENTION

This invention provides a method for identifying cells expressing a target single chain antibody (scFv) directed against a target antigen from a collection of cells that includes cells that do not express the target scFv, comprising the step of combining the collection of cells with an anti-idiotype directed to an antibody specific for the target antigen and detecting interaction, if any, of the anti-idiotype with the cells, wherein the occurrence of an interaction identifies the cell as one which expresses the target scFv.

This invention also provides a method for inducing proliferation in a population of T cells comprising the steps of (a) introducing to the T cells an expressable gene sequence encoding a scFv coupled to a transmembrane and signaling domain; and (b) exposing the T cells to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv thereby inducing proliferation of the T cells.

This invention further provides a method for treating cancer in a patient suffering from cancer expressing an antigenic marker comprising the steps of removing lymphocytes from the patient, introducing to the lymphocytes an expressable gene sequence encoding a chimeric scFv coupled to a transmembrane and signaling domain; exposing the lymphocytes to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv and any necessary co stimulatory molecules to induce proliferation of the lymphocytes; and returning the expanded population of lymphocytes to the patient.

In addition, this invention provides a method for treating cancer in a patient suffering from cancer expressing an antigenic marker comprising the steps of introducing to human cell lines an expressable gene sequence encoding a chimeric scFv coupled to a transmembrane and signaling domain (including zeta chain); exposing the lymphocytes to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv and any necessary co stimulatory molecules to immunoselect and stimulate clones with high density of scFv expression and efficient tumor cytotoxicity to produce a gene-modified cell line, and returning the expanded population of gene-modified cell line to the patient.

This invention also provides a method for enhancing in vivo survival and anti-tumor activity of infused lymphocytes gene-modified with scFv-Chimeric immune receptors by intravenous injection of anti-idiotype antibody. This invention further provides compositions containing scFv, scFv fusion, cells identified, induced T cell population, alone or in combination thereof.

Finally, this invention provides various uses of the above methods and compositions.

DETAILED DESCRIPTION OF THE FIGURES

First Series of Experiments

FIG. **1**. Inhibition of 8H9 by anti-idiotype 2E9 by FACS analysis. **1**A: Staining of LAN-1 neuroblastoma cells with 5 ug/ml of 8H9 (shaded peak) was not inhibited at low concentration of 2E9 (2 ug/ml, black solid line), but almost completely at concentration of 10 ug/ml (dotted line) superimposable with the negative antibody control (grey solid line). **1**B: Staining of LAN-1 neuroblastoma cells with 5 ug/ml of 3F8 (anti-GD2, shaded peak) was not inhibited by any concentrations (2 ug/ml, black solid line, or 200 ug/ml, dotted line) of 2E9; negative antibody control thin solid line. **1**C: Staining of HTB-82 rhabdomyosarcoma cells with 5 ug/ml of 8H9 (grey peak) was not inhibited at low concentration (2 ug/ml, grey solid line), but completely at 10 ug/ml of 2E9 (black solid line) superimposable with negative antibody control (black peak).

FIG. **2**. SDS-PAGE (lanes a and b) and Western blot (c and d) of ch8H9. H=heavy chain of 8H9, L=light chain of 8H9, arrow points to ch8H9, the fusion protein between 8H9 scFv and the human 1-CH2-CH3 domain. With 2-mercaptothanol: lanes a, b and c. Native gel: lane d. SDS-PAGE was stained with Comassie Blue; western blot with 2E9 anti-idiotypic antibody.

FIG. **3**. FACS analysis of ch8H9 and 8H9 staining of HTB82 rhabdomyosarcoma and LAN-1 neuroblastoma cells. Mean immunofluorescence increased with concentrations of ch8H9 and 8H9, reaching a plateau around antibody concentration of 3-5 ug/ml. Left Y-axis is mean fluorescence for native 8H9, and the right Y-axis depicts mean fluorescence for ch8H9. Stronger fluorescence for native 8H9 reflects a stronger second antibody.

FIG. **4**. ch8H9 in antibody-dependent cell-mediated cytotoxicity. ADCC was measured by ^{51}Cr release as described in Materials and Methods. Percent specific release is depicted as mean+/−SEM. Target cell line was rhabdomyosarcoma HTB-82. Control antibody was 3F8 which binds poorly to HTB-82.

FIG. **5**. Immunoscintigraphy of human tumors using ^{125}I-labeled ch8H9. Mice xenografted with human LAN-1 neuroblastoma received retroorbital injections of 25 uCi of ^{125}I-labeled antibody. 24 h, 48 h and 7 days after injection, the animals were anesthesized and imaged with a gamma camera.

FIG. **6**. Blood clearance of ^{125}I-labeled ch8H9 and ^{125}I-native 8H9. Mice xenografted with human LAN-1 neuroblastoma received retroorbital injections of ^{125}I-labeled antibody. Percent injected dose/gm of serial blood samples were plotted over time.

Second Series of Experiments

FIG. **7**. Anti-idiotype affinity enrichment of producer lines. Producer lines were stained with anti-idiotypic MoAb 2E9 before (shaded peak, **7**A and **7**B), and after first (dotted line peak, **7**A) and second (thick solid line, **7**A) affinity purification, and after first (dotted line, **7**B) and second (solid line **7**B) subcloning, showing improved scFv expression. By FACS the indicator line K562 showed improved scFv expression after first (dotted line, **7**C) and second (thick solid line, **7**C) affinity purification of the producer line, and subsequent first (dotted line, **7**C) and second (thick solid line, **7**D) subcloning of the producer line, when compared to unpurified producer lines (shaded peaks, **7**C and **7**D), consistent with improvement in gene transduction efficiency. The thin solid line curves in each figure represents nonproducer line (**7**A and **7**B) or uninfected K562 (**7**C and **7**D).

FIG. **8**. In vitro expansion of 8h9-scfv-CD28-ζ gene-modified primary human lymphocytes depends on stimulation with anti-idiotypic antibody. Clonal expansion was expressed as fold expansion of initial viable lymphocyte number. Il-2 (100 u/ml [FIG. **8***a*], 50 u/ml [FIG. **8***b*] and 20 u/ml [FIG. **8***c*]) was added after retroviral infection and was present throughout the entire in vitro culture period, in the presence (solid circles) or absence (open circles) of solid-phase anti-idiotypic antibody. Viable cell count was performed using trypan blue assay.

FIG. **9**. In vitro expansion of 8H9-scFv-CD28-ζ gene-modified primary human lymphocytes from 4 patients with stage 4 neuroblastoma (FIG. **9**A) and 4 samples from 2 normal volunteers (FIG. **9**B). Clonal expansion was expressed as fold expansion of initial viable lymphocyte number before in vitro culture. IL-2 (100 U/ml) and anti-idiotype antibodies were present as described in Materials and Methods. 8H9-scFv-CD28-ζ gene-modified lymphocytes underwent continual clonal expansion (103 to 108), and survived 150-200 days in vitro, with a double time of ~5-10 days.

FIG. **10**. Kinetics of clonal dominance by scFv+ cells and its relationship to 8H9scFv gene copy number and 8H9scFv transcript. Percent of lymphocytes positive for surface scFv was monitored by flow cytometry using anti-idiotype antibody (FIG. **10**A); it rapidly increased to near 100% by 3 weeks of culture. ScFv gene copy number (PCR, open circles, broken line, FIG. **10**B) and scFv transcript (RT-PCR, solid diamonds, solid line, FIG. **10**B) also increased with time, reaching their plateau by 10 weeks in culture.

FIG. **11**. Cytotoxicity against tumor cell lines: 8H9-scFv-CD28-ζ gene-modified lymphocytes (solid circles) from day of culture were assayed by 51Cr release assay in the presence or absence of MoAb 8H9 (50 ug/ml final concentration) as an antigen blocking agent (open circles). Control lymphocytes from the same donor but not gene-modified, were cultured under the same conditions as the gene-modified cells, and tested in cytotoxicity assays in the presence (open diamonds) or absence (solid diamonds) of MoAb 8H9. **11**A: NMB-7 neuroblastoma. **11**B: LAN-1 neuroblastoma. **11**C: HTB-82 rhabdomyosarcoma. **11**D: Daudi lymphoma.

FIG. **12**. Winn assay. Suppression of rhabdomyosarcoma tumor growth in scid mice. Human rhabdomyosarcoma HTB-82 was strongly reactive with 8H9, but not with 5F11 (anti-GD2) antibodies. Experimental groups: HTB-82 was mixed with 8H9-scfv-CD28-ζ gene-modified human lymphocytes at 3 ratios: 1:0.5 (open circle, n=5), 1:1 (solid triangle, n=5), 1:10 (open square, n=10). Control groups: no T-cell (open triangles, n=5), 5F11scfv-CD28-ζ modified lymphocytes at 1:0.5 ratio (solid circles, n=5). Tumor size was calculated as product of two perpendicular diameters a×b (mean±sem) and plotted over time.

FIG. **13**. Suppression of established rhabdomyosarcoma tumor growth in SCID mice. Experimental group: 8H9-scFv-CD28-ζ gene-modified human lymphocytes+ip 2E9 [rat anti-8H9 anti-idiotype MoAb] (solid circles). Control groups: no cells (open triangles), 5F11scFv-CD28-ζ modified lymphocytes+1G8 [rat anti-5F11 anti-idiotype MoAb] (solid squares), and 8H9-scFv-CD28ζ gene-modified human lymphocytes+ip A1G4 [irrelevant rat class-matched MoAb] (open circles). Relative tumor size was calculated as % of initial tumor size (A×B, mean±sem, n=9-10) and plotted over time.

Third Series of the Experiments

FIG. **14**. Transduction of HSV1-tk into primary human T-cells HSV1-tk is a therapeutic gene, a marker gene, as well as a suicide gene. In order to examine the migration of genetically altered antigen-specific t lymphocytes to tumors after adoptive transfer in vivo, we exploited the capacity of transduced T cells expressing HSV-TK to selectively phosphorylate and trap in cells and incorporate into DNA radiolabeled thymidine analog 2'-fluoro-2'deoxy-1-d-arabinofuransyl-5-iodo-uracil.

FIG. **15**. I131-FIAU absorbed dose to lymphocyte cell nuclei. Based on the forgoing dosimetry model and as presented graphically in this figure, the lymphocyte nucleus absorbed dose was calculated as a function of activity concentration in the medium and the accumulation ratio. To study the effect on T-cell function, [^{131}I]-labeled FIAU was incubated with HSV1-tk transduced T cells at 11 ci/ml at 37° C. for 40 to 120 min in increasing activity concentrations of [^{131}I]-FIAU from 1.1 to 56 μci/ml, washed and transferred to fresh ([^{131}I]-FIAU-free) medium for 72 hr, and then used in a ^{51}CR-release immune cytotoxicity assay (low effector:target cell ratio=5). There was no demonstrable diminution in immune function up to an absorbed dose (at the reference time of 60 hr) of 1,200 cGy. At greater doses (>1,900 cGy), there was a dose-dependent decrease in immune function.

FIG. **16**. Structure of DOTA-DPhe^1-Tyr^3-octreotide (DOTATOC). Radioactive gallium labeled somatostatin analogue DOTA-DPhe^1-Tyr^3-octreotide (DOTATOC) for positron emission tomography imaging. Radionuclide labeled somatostatin analogues selectively target somatostatin receptor (SSTR)-expressing tumors as a basis for diagnosis and treatment of these tumors. Recently, a DOTA-functionalized somatostatin analogue, DOTATOC has been developed. This compound has been shown to be superior to the other somatostatin analogues as indicated by its uniquely high tumor-to-nontumor tissue ratio. DOTATOC can be labeled with a variety of radiometals including gallium radioisotopes. Gallium-66 is a positron emitting radionuclide ($T_{1/2}$=9.5 hr; β^+=56%) that can be produced in carrier free form by a low-beam energy cyclotron.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a method for making a single chain antibody (scFv) directed against a specific, but not necessarily isolated antigen. The invention further provides a method for identifying cells expressing the target scFv directed against the antigen, and a method for enriching cell populations expressing the target scFv, and for promoting proliferation and expansion of such populations. The invention makes use of an anti-idiotype antibody which is directed to an antibody specific for the antigen. Cells expressing the scFv are recognized by the anti-idiotype, thus allowing their selection. Furthermore, where the scFV is a chimeric immune receptor, which includes a signaling domain in addition to the scFv, the anti-idiotype ligates to these receptors and stimulates proliferation of scFV expressing T-cells.

The generic invention is illustrated with reference to a specific antibody, designated 8H9, of which the antigen is gp58. 8H9 is a murine IgG1 monoclonal antibody specific for a novel antigen on the cell surface of a wide spectrum of human solid tumors, but not on normal tissues. In accordance with the invention, scFv directed against gp58 antibody was prepared using an anti-idiotype directed against the anti-8H9 monoclonal antibody.

In a first aspect, the present invention provides a method for identifying cells expressing a target single chain antibody (scFv) directed against a target antigen from a collection of cells that includes cells that do not express the target scFv. In a second aspect, the present invention provides a method for making an scFv. In each of these aspects of the invention, an anti-idiotype directed against an antibody that is itself directed against the target antigen is utilized.

As used in the specification and claims of this application, the term "directed against" refers to the binding specificity of an antibody. An antibody which is directed against a particular antigen is one which was developed and/or selected by a procedure which involves immunization of an animal with the antigen and/or testing of the antibody for binding with the antigen. The antibody may associate with one or a plurality of epitopes of the target antigen, and may be polyclonal or monoclonal. The term "directed against" does not exclude the possibility of cross-reactivity with other antigens, although antibodies with substantial specificity for the particular target antigen are preferred.

Antibodies directed against the target antigen may be prepared using conventional techniques, including techniques which do not require isolation or specific knowledge of the antigen. In general, an antigen or a sample for which an antibody is to be developed is administered to an organism to stimulate an immune response. For example, cancer tissue samples against which it would be desirable to have an antibody can be administered to mice. Monoclonal antibodies can be developed by fusion of splenic lymphocytes from such immunized mice to myeloma cells to produce a hybridoma. Selection of hybridoma's producing monoclonal antibodies of the desired specificity is carried out in a routine manner by testing for the ability to bind to the original target tissue.

Using this general technique, Applicants have isolated a monoclonal antibody designated 8H9. As described in Modak et al., *Cancer Res.* 61: 4048-4054 (2001), monoclonal antibody 8H9 is a murine IgG1 hybridoma derived from the fusion of mouse myeloma SP2/0 cells and splenic lymphocytes from BALE/c mice immunized with human neuroblastoma. By immunohistochemistry, 8H9 was highly reactive with human brain tumors, childhood sarcomas, and neuroblastomas, and less so with adenocarcinomas. Among primary brain tumors, 15 of 17 glioblastomas, 3 of 4 mixed gliomas, 4 of 11 oligodendrogliomas, 6 of 8 astrocytomas, 2 of 2 meningiomas, 3 of 3 schwannomas, 2 of 2 medulloblastomas, 1 of 1 neurofibroma, 1 of 2 neuronoglial tumors, 2 of 3 ependymomas, and 1 of 1 pineoblastoma tested positive. Among sarcomas, 21 of 21 Ewing's/primitive neuroectodermal tumor, 28 of 29 rhabdomyosarcomas, 28 of 29 osteosarcomas, 35 of 37 desmoplastic small round cell tumors, 2 of 3 synovial sarcomas, 4 of 4 leiomyosarcomas, 1 of 1 malignant fibrous histiocytoma, and 2 of 2 undifferentiated sarcomas tested positive with 8H9. Eighty-seven of 90 neuroblastomas, 12 of 16 melanomas, 3 of 4 hepatoblastomas, 7 of 8 Wilms' tumors, 3 of 3 rhabdoid tumors, and 12 of 27 adenocarcinomas also tested positive. In contrast, 8H9 was nonreactive with normal human tissues including bone marrow, colon, stomach, heart, lung, muscle, thyroid, testes, pancreas, and human brain (frontal lobe, cerebellum, pons, and spinal cord). Reactivity with normal cynomolgus monkey tissue was restricted similarly. Indirect immunofluorescence localized the antigen recognized by 8H9 to the cell membrane.

These characteristics of the antigen recognized by mAB 8H9 ("8H9-antigen") made it a strong potential candidate as a therapeutic target. 8H9 immunoprecipitated a Mr 58,000 band after N-glycanase treatment, most likely a protein with a heterogeneous degree of glycosylation. However, the antigen is proteinase sensitive and is not easily modulated off the cell surface. Thus, preparation and isolation of an scFv which could be used for targeting cells expressing the 8H9-antigen required the development of a different approach.

In accordance with the method of the present invention, the antibody directed against the target antigen is used to create an anti-idiotype antibody. The anti-idiotype antibody can be produced in any species, including human (preferably using in vitro immunization), although mouse and rat will most commonly be immunized because of the convenience of working with such animals in the laboratory. The anti-idiotype is preferably prepared as a monoclonal antibody to make it easier to produce or purify. Once made, the anti-idiotype can be used to screen scFv libraries from any species to identify scFv antibodies directed against the target of the original antibody used to create the anti-idiotype. Thus, as illustrated in the examples below, a rat anti-mouse idiotype was used to screen a human cDNA scFv library.

The procedures for creating scFv libraries are known in the art. Generally, the procedures involve amplification of the variable regions of nucleic acids encoding an antibody, commonly from a hybridoma producing an antibody of interest. Generic primers associated with the constant regions of such antibodies are available commercially. The amplified fragments are then further amplified with primers selected to introduce appropriate restriction sites for introduction of the scFv into an expression vector, phage, or fusion protein. Cells producing the scFv are screened and an scFv with the desired selectivity is identified.

The scFv which is identified can be used in any of numerous applications. For example, the scFv can be labeled, for example using a radiolabel, a colored or chromogenic label or a fluorescent label, and used for diagnostic testing of tissue samples to detect the presence of a tumor-associated target antigen (such as the 8H9-antigen) or other diagnostic antigenic marker. Tissue samples are exposed to the labeled scFv for a period of time to allow specific interaction if the target antigen is present. The sample is washed to remove non-specifically bound materials, and binding of the label to the cells is indicative of the presence of the marker. A similar approach may be used for histological mapping of the location of antigenic markers in tissue sections and samples. The scFv may also be used as one component in sandwich type assays, such as ELISA, and may be used as affinity probes for capture and purification of the target antigen.

The scFv may be used as a targeting moiety to direct chemotherapy agents to specific cell types. The DNA encoding the scFv may also be combined to produce a genetic sequence encoding a fusion protein. Examples of types of fusion proteins which may be created include scFv-cytokine (Shu et al., *Proc. Nat'l Acad. Sci.* (*USA*) 90: 7995-7999 (1993), scFv-streptavidin (Kipriyanov et al., *Human Antibody Hybridomas* 6: 93-101 (1995); WO 97/34634), scFv-enzyme (Michael et al., *Immunotech.* 2: 47-57 (1996)), scFv-toxin (Wickstrand et al., *Cancer Res.* 55: 3140-48 (1995)), bispecific scFv (diabodies) (Alt et al., *FEBS Letters* 454: 90-94 (1999)), bi-specific chelating scFv (De Nardo et al., *Clin., Cancer Res.* 5: 3213s-3218s (1999)), scFv-Ig (Shu et al., supra), tetravalent scFv (Alt et al., supra, Santos et al., *Clin., Cancer Res.* 5: 3118s-3123s (1999)), and scFv-retargeted T cells (Eshar et al., *Proc. Nat'l Acad. Sci* (*USA*) 90: 720-724 (1993)).

In one specific embodiment of the invention, the scFv is coupled in a fusion protein to T-cell signaling and transmembrane domains. Expression of such fusion proteins in T cells leads to presentation of the scFv on the surface of the T cell. Proliferation and expansion of such T cells can be induced by exposing the T cells to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv. Furthermore, such T cells will be targeted in vivo to cells which express the target antigen. Thus, the present invention also provides a method for treating a disease condition characterized by the presence of cells expressing a characteristic surface antigen, comprising the steps of developing an scFv to the target antigen and forming a genetic sequence encoding a fusion protein of the scFv with T cell signaling and transmembrane domains; recovering lymphocytic cells from the patient and transforming the cells ex vivo so that they express the fusion protein, stimulating proliferation and expansion of the cells by exposing the cells ex vivo to an anti-idiotype, and returning the cells to the patient.

This invention also provides compositions comprising the scFv, scFv fusion, and cells expressing scFv, respectively. This invention provides a pharmaceutical composition comprising scFv alone, scFv fusion alone, cells expressing scFv alone, or any combination thereof. This invention further provides a pharmaceutical composition comprising scFv alone, scFv fusion alone, cells expressing scFv alone, or any combination thereof and a pharmaceutically acceptable carrier. For the purposes of this invention, "pharmaceutically acceptable carriers" means any of the standard pharmaceutical carriers. Examples of suitable carriers are well known in the art and may include, but are not limited to, any of the standard pharmaceutical carriers such as a phosphate buffered saline solution and various wetting agents. Other carriers may include additives used in tablets, granules and capsules, etc. Typically such carriers contain excipients such as starch, milk, sugar, certain types of clay, gelatin, stearic acid or salts thereof, magnesium or calcium stearate, talc, vegetable fats or oils, gum, glycols or other known excipients. Such carriers may also include flavor and color additives or other ingredients. Compositions comprising such carriers are formulated by well-known conventional methods.

The invention will be better understood by reference to the Experimental Details which follow, but those skilled in the art will readily appreciate that the specific experiments detailed are only illustrative, and are not meant to limit the invention as described herein, which is defined by the claims which follow thereafter.

From these and the foregoing description, it can be seen that the invention provides:

A method for identifying cells expressing a target scFv directed against a target antigen from a collection of cells that includes cells that do not express the target scFv, comprising the step of combining the collection of cells with an anti-idiotype directed to an antibody specific for the target antigen and detecting interaction, if any, of the anti-idiotype with the cells, wherein the occurrence of an interaction identifies the cell as one which expresses the target scFv. The cells identified by the above method. A composition comprising said cells.

A method for making a scFv directed against an antigen, wherein the selection of clones is made based upon interaction of those clones with an appropriate anti-idiotype, and heretofore inaccessible scFv so made.

The single chain antibody made by the above method and a composition comprising said scFv.

A method for selecting cell lines that package and produce high titers of retroviral particles that carry the scFv gene for transfection into cells. The cells include but are not limited to human lymphocytes.

The selected cell lines from the above method and composition comprising the same.

A method for inducing proliferation in a population of T cells comprising the steps of (a) introducing to the T cells an expressable gene sequence encoding a chimeric scFv coupled to a transmembrane and signaling domain; and (b) exposing the T cells to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv thereby inducing proliferation of the T cells.

The population of T cells induced by the above method and composition comprising the same.

A method for tagging cells to facilitate sorting or enrichment, comprising the steps of expressing a scFv in the cell and capturing or tagging the cells using anti-idiotype.

A method for isolating an antigen comprising the steps of preparing an antibody to the antigen, preparing an anti-idiotype directed to the antibody, using the anti-idiotype to select a scFv, targeting the antigen from a scFv library, and using the selected scFv as an affinity probe to capture antigen, preferably with the scFv immobilized on a solid support.

The isolated antigen by the above method and a composition comprising the same.

A method for treating cancer in a patient suffering from cancer expressing an antigenic marker comprising the steps of removing lymphocytes from the patient, introducing to the lymphocytes an expressable gene sequence encoding a chimeric scFv coupled to a transmembrane and signaling domain; exposing the lymphocytes to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv and any necessary co stimulatory molecules to induce proliferation of the lymphocytes; and returning the expanded population of lymphocytes to the patient. The antigenic marker includes but is not limited to gp58 and GD2.

A method for treating cancer in a patient suffering from cancer expressing an antigenic marker comprising the steps of introducing to human cell lines an expressable gene sequence encoding a chimeric single chain antibody (scFv) coupled to a transmembrane and signaling domain (including zeta chain); exposing the lymphocytes to which the chimeric scFv has been introduced to an anti-idiotype directed to an antibody specific for a target antigen to which the scFv is directed under conditions such that the anti-idiotype will bind to scFv on the surface of cells expressing the chimeric scFv and any necessary co stimulatory molecules to immunoselect and stimulate clones with high density of scFv expression and efficient tumor cytotoxicity to produce a gene-modified cell line, and returning the expanded population of gene-modified cell line to the patient. The antigenic marker includes but is not limited to GD2 and gp58. The human cell line includes but is not limited to NK92, natural killer, helper, and cytotoxic cell line. The gene-modified cell line produced by the above method. A composition comprising the gene-modified cell line.

A method for enhancing in vivo survival and anti-tumor activity of infused lymphocytes gene-modified with scFv-Chimeric immune receptors by intravenous injection of anti-idiotype antibody.

EXPERIMENTAL DETAILS

First Series of Experiments

Anti-Idiotypic Antibody as the Surrogate Antigen for Cloning scFv and Its Fusion Proteins

ScFv is a versatile building block for novel targeting constructs. However, a reliable screening and binding assay is often the limiting step for antigens that are difficult to clone or purify. We demonstrate that anti-idiotypic antibodies can be used as surrogate antigens for cloning scFv and their fusion proteins. 8H9 is a murine IgG1 monoclonal antibody specific for a novel antigen expressed on the cell surface of a wide spectrum of human solid tumors but not in normal tissues (Cancer Res 61:4048, 2001) Rat anti-8H9-idiotypic hybridomas (clones 2E9, 1E12 and 1F11) were produced by somatic cell fusion between rat lymphocytes and mouse SP2/0 myeloma. In direct binding assays (ELISA) they were specific for the 8H9 idiotope. Using 2E9 as the surrogate antigen, 8H9-scFv was cloned from hybridoma cDNA by phage display. 8H9scFv was then fused to human-γ1-CH2-CH3 cDNA for transduction into CHO and NSO cells. High expressors of mouse scFv-human Fc chimeric antibody were selected. The secreted homodimer reacted specifically with antigen-positive tumor cells by ELISA and by flow cytometry, inhibitable by the anti-idiotypic antibody. The reduced size resulted in a shorter half-life in vivo, while achieving comparable tumor to nontumor ratio as the native antibody 8H9. However, its in vitro activity in antibody-dependent cell-mediated cytotoxicity was modest.

Introduction

Single chain Fv (scFv) has greatly expanded the potential and development of antibody-based targeted therapies.(1-4) Using phage display, scFv can now be cloned from cDNA libraries derived from rodents, immunized volunteers, or patients.(5-8) The availability of hIg-transgenic and transchromosomal mice will allow immunization schema or pathogens not feasible or safe in humans.

Construction of the scFv is the critical first step in the synthesis of various fusion proteins, including scFv-cytokine,(9) scFv-streptavidin,(10) scFv-enzyme,(11) scFv-toxins,(12) bispecific scFv (diabodies),(13) bispecific chelating scFv,(14) scFv-Ig,(9) tetravalent scFv(13,15) and scFv-retargeted T-cells. ScFv-Ig constructs mimic natural IgG molecules in their homodimerization through the Fc region, as well as their ability to activate complement (CMC) and mediate antibody dependent cell-mediated cytotoxicites (ADCC).

The construction of scFv requires a reliable antigen preparation both for panning phages and for binding assays. They often become a rate-limiting step,(17) particularly for antigens that are difficult to clone or purify. Cell-based phage display,(18) and enzyme linked immunosorbent assays (ELISA) when optimized, have been successfully applied as alternatives. Subtle differences in the panning step can determine the success or failure of phage display.(19) For example, a reduction in wash pH is needed for scFv directed at ganglioside GD2 in order to reduce nonspecific adherence of phage particles.(19) Moreover, phage binding assay may require membrane preparations to withstand the vigorous washing procedure.

As antigen mimics of infectious agents and tumor antigens, anti-idiotypic antibodies have promising clinical potentials.(20-22) They are convenient surrogates when the target antigen is not readily available. The physico-chemical behavior of immunoglobulins as antigens in panning and binding assays is generally known and can be easily standardized. Hombach et al successfully isolated scFv with specificity for CD30 utilizing internal image anti-idiotypic antibodies.(23) We recently described a novel tumor antigen reactive with a murine MoAb 8H9.(24) Given its lability and glycosylation, this antigen is difficult to purify. Here we describe the use of an anti-idiotypic antibody as a surrogate antigen for cloning a scFv derived from the 8H9 hybridoma cDNA library, and for the selection of chimeric mouse scFv-human Fc fusion constructs. This provides a proof of principle for isolating antibodies of same specificity from a non-specific phage display library.

Materials and Methods

Animals

BALE/c mice were purchased from Jackson Laboratories, Bar Harbor, Me. Lou/CN rats were obtained from the National Cancer Institute-Frederick Cancer Center (Bethesda, Md.) and maintained in ventilated cages. Experiments were carried out under a protocol approved by the Institutional Animal Care and Use Committee, and guidelines for the proper and humane use of animals in research were followed.

Cell Lines

Human neuroblastoma cell lines LAN-1 was provided by Dr. Robert Seeger (Children's Hospital of Los Angeles, Los Angeles, Calif.), and NMB7 by Dr. Shuen-Kuei Liao (McMaster University, Ontario, Canada). Cell lines were cultured in 10% defined calf serum (Hyclone, Logan, Utah) in RPMI with 2 mM L-glutamine, 100 U/ml of penicillin (Sigma-Aldrich, St. Louis, Mo.), 100 ug/ml of streptomycin (Sigma-Aldrich), 5% CO_2 in a 37° C. humidified incubator. Normal human mononuclear cells were prepared from heparinized bone marrow samples by centrifugation across a Ficoll-Hypaque density separation gradient. Human AB serum (Gemini Bioproducts, Woodland, Calif.) was used as the source of human complement.

Monoclonal Antibodies

Cells were cultured in RPMI 1640 with 10% newborn calf serum (Hyclone, Logan, Utah) supplemented with 2 mM glutamine, 100 U/ml of penicillin and 100 ug/ml of streptomycin (Sigma-Aldrich). 3F8, an IgG3 MoAb raised in a BALE/c mouse against human neuroblastoma, specifically recognizes the ganglioside GD2. The BALE/c myeloma proteins MOPC-104E, TEPC-183, MOPC-351, TEPC-15, MOPC-21, UPC-10, MOPC-141, FLOPC-21, and Y5606 were purchased from Sigma-Aldrich. MoAb R24 (anti-GD3), V1-R24, and K9 (anti-GD3) were gifts from Dr. A. Houghton, OKB7 and M195 (anti-CD33) from Dr. D. Scheinberg, and 10-11 (anti-GM2) from Dr. P. Livingston of Memorial Sloan Kettering Cancer Center, New York; and 528 (EGF-R) from Dr. J. Mendelsohn of MD Anderson, Houston, Tex. 2E6 (rat anti-mouse IgG3) was obtained from hybridomas purchased from American Type Culture Collection [ATCC] (Rockville, Md.). NR-Co-04 was provided by Genetics Institute (Cambridge, Mass.). In our laboratory, 5F9, 8H9, 3A5, 3E7, 1D7, 1A7 were produced against human neuroblastoma; 2C9, 2E10 and 3E6 against human breast carcinoma, and 4B6 against glioblastoma multiforme. They were all purified by protein A or protein G (Pharmacia, Piscataway, N.J.) affinity chromatography.

Anti-8H9 Anti-Idiotypic Antibodies

LOU/CN rats were immunized intraperitoneally (ip) with 8H9 (400 µg per rat) complexed with rabbit anti-rat serum (in 0.15 ml), and emulsified with an equal volume (0.15 ml) of Complete Freund's Adjuvant (CFA) (Gibco-BRL, Gaithersburg, Md.). The 8H9-rabbit-IgG complex was prepared by mixing 2 ml (8 mg) of purified 8H9 with 4 ml of a high titer rabbit anti-rat precipitating serum (Jackson Immunoresearch Laboratories, West Grove, Pa.). After incubation at 4° C. for 3 hours, the precipitate was isolated by centrifugation at 2500 rpm for 10 minutes, and resuspended in PBS. Three months after primary immunization, the rats were boosted ip with the same antigen in CFA. One month later, a 400 µg boost of 8H9-rabbit-anti-mouse complex was injected intravenously. Three days afterwards, the rat spleen was removed aseptically, and purified lymphocytes were hybridized with SP2/0-Ag14 (ATCC). Clones selection was based on specific binding to 8H9 and not to control antibody 5F9, a murine IgG1. Repeated subcloning using limiting dilution was done. Isotypes of the rat monoclonal antibodies were determined by Monoclonal Typing Kit (Sigma-Aldrich). Rat anti-idiotypic antibody clones (2E9, 1E12, 1F11) were chosen and produced by high density miniPERM bioreactor (Unisyn technologies, Hopkinton, Mass.), and purified by protein G affinity chromatography (Hitrap G, Pharmacia). The IgG fraction was eluted with pH 2.7 glycine-HCl buffer and neutralized with 1 M Tris buffer pH 9. After dialysis in PBS at 4° C. for 18 hours, the purified antibody was filtered through a 0.2 um millipore filter (Millipore, Bedford, Mass.), and stored frozen at −70° C. Purity was determined by SDS-PAGE electrophoresis using 7.5% acrylamide gel. 2E9 was chosen from among the three anti-idiotypic antibodies because of its high titer.

The "standard" ELISA to detect rat anti-idiotypic antibodies (Ab2) was as follows: Purified 8H9, or irrelevant IgG1 myeloma, were diluted to 5 ug/ml in PBS and 50 µl per well was added to 96-well flat-bottomed polyvinylchloride (PVC) microtiter plates and incubated for 1 hour at 37° C. Rows with no antigen were used for background subtraction. Filler protein was 0.5% BSA in PBS and was added at 100 µl per well, and incubated for 30 minutes at 4° C. After washing, 50 µl duplicates of hybridoma supernatant was added to the antigen-coated wells and incubated for 3 hours at 37° C. The plates were washed and a peroxidase-conjugated mouse anti-rat IgG+IgM (Jackson Immunoresearch Laboratory) at 100 µl per well was allowed to react for 1 hour at 4° C. The plate was developed using the substrate o-phenylenediamine (Sigma-Aldrich) (0.5 mg/ml) and hydrogen peroxide (0.03%) in 0.1 M citrate phosphate buffer at pH 5. After 30 minutes in the dark, the reaction was quenched with 30 µl of 5 N sulfuric acid and read using an ELISA plate reader.

Specificity by Direct Binding Assay

Fifty µl per well of purified mouse monoclonal antibodies or myelomas were coated onto 96-well PVC microtiter plates at 5 ug/ml for 60 minutes at 37° C., aspirated and then blocked with 100 µl of 0.5% BSA filler protein per well. After washing and air-drying, the wells were allowed to react with anti-idiotypic antibodies. The rest of the procedure was identical to that described in the "standard" assay.

Specificity by Inhibition Assay

To further examine the specificity of these anti-idiotypic antibodies, inhibition of 8H9 immunofluorescent staining of tumor cells by anti-idiotypic antibodies was tested. Purified 8H9 and anti-GD2 MoAb 3F8, (all 10 ug/ml in 0.5% BSA) were preincubated with various concentrations of anti-idiotypic antibodies for 30 minutes on ice before reacting with 10^6 cells of either GD2-positive/8H9 positive LAN-1 (neuroblastoma) or GD2-negative/8H9-positive HTB-82 (rhabdomyosarcoma). The cells were then washed twice in PBS with 0.1% sodium azide and reacted with FITC-conjugated rat anti-mouse IgG (Biosource, Burlingame, Calif.) on ice for 30 minutes in the dark. The cells were washed in PBS with azide, fixed in 1% paraformaldehyde and analyzed by FACScan (Becton-Dickinson, Calif.). The mean fluorescence was calculated and the inhibition curve computed.

Construction of scFv Gene

mRNA was isolated from 8H9 hybridoma cells using Quick Prep Micro mRNA Purification kit (Pharmacia Biotech). 5×10^6 hybridoma cells cultured in RPMI-1640 medium supplemented 10% calf serum, L-glutamine (2 mmol/L), penicillin (100 u/L) and streptomycin sulphate (100 ug/ml) were pelleted by centrifugation at 800×g and washed once in RNase-free phosphate buffered saline (pH 7.4). Cells were lysed directly in the extraction buffer and Poly(A)-RNA was purified by oligo (dT)-cellulose. The mRNA sample was precipitated from the elution buffer using 100 µg glycogen, 40 µl of 2M potassium acetate solution and 1 ml of absolute ethanol at −20° C. for 1 hour. The nucleic acid was recovered by centrifugation at 10,000×g for 30 min. The sample was evaporated until dry, and dissolved in 20 µl RNase-free water.

ScFv gene was constructed by recombinant phage display. 5 µl of mRNA was reverse-transcribed in a total volume of 11 µl reaction mixture and 1 µl dithiothreitol (DTT) solution for 1 hour at 37° C. For PCR amplification of immunoglobulin variable regions, light chain primer mix and the heavy chain primer sets (Pharmacia) were added, to generate suitable quantities of the heavy (340 bp) and light (325 bp) chains. Following an initial 10 min dwell at 95° C., 5 U AmpliTaq Gold DNA polymerase (Applied Biosystems, Foster City, Calif.) was added. The PCR cycles consisted of a 1 min denaturation step at 94° C., a 2 min annealing step at 55° C. and a 2 min extension step at 72° C. After 30 cycles of amplification, PCR derived fragment was purified by the glassmilk beads (Bio101, Vista, Calif.) and separated by 1.5% agarose gel electrophoresis in TAE buffer, then visualized by ethidium bromide staining. For the assembly and fill-in reaction, both purified heavy chain and light chain fragments were added to an appropriate PCR mixture containing a 15 amino acid linker-primer for 8H9, dNTPs, PCR buffer and Ampli Taq Gold DNA polymerase. PCR reactions were performed at

94° C. for 1 min, followed by a 4 min annealing reaction at 63° C. The heavy and light chain DNA of 8H9 were joined by the linker $(GGGS)_3$ (Pharmacia) into scFv in a VH-VL orientation after 7 thermocycles. Using an assembled scFv DNA of 8H9 as template, a secondary PCR amplification (30 standard PCR cycles) was carried out using primers containing either Sfi I or Not I restriction sites. Thus, the Sfi I and Not I restriction sites were introduced to the 5' end of heavy chain and the 3' end of light chain, respectively. Amplified ScFv DNAs were purified by glassmilk beads and digested with Sfi I and Not I restriction endonucleases. Digestion with Sfi I was carried out in NEBuffer (50 mM NaCl, 10 mM Tris-HCl, 10 mM $MgCl_2$, 1 mM Dithiothreitol, pH 7.9) for 4 hours at 50° C. NotI digestion was carried out in 100 mM NaCl for 4 hours at 37° C. The purified ScFv of 8H9 was inserted into the pHEN1 vector (kindly provided by Dr. G. Winter, Medical Research Council Centre, Cambridge, UK) containing Sfi I/Nco I and Not I restriction sites. Competent *E. coli* XL 1-Blue cells (Stratagene, La Jolla, Calif.) were transformed with the pHEN1 phagemid. Helper phage M13 KO7 (Pharmacia) was added to rescue the recombinant phagemid.

Enrichment of recombinant phagemid by panning 50 µl of anti-8H9 idiotypic antibody 2E9 (50 ug/ml) in PBS was coated on the 96-well PVC microtiter plates and incubated at 37° C. for 1 hour. 100 µl of the supernatant from phage library was added to each well and incubated for 2 hours. The plate was washed 10 times with PBS containing 0.05% BSA. Antigen-positive recombinant phage captured by the anti-idiotype MoAb 2E9 was eluted with 0.1M glycine-HCl (pH 2.2 containing 0.1% BSA) and neutralized with 2M Tris solution. This panning procedure was repeated three times. The phagemid 8HpHM9F7-1 was chosen for the rest of the experiments.

ELISA

The selected phage was used to reinfect *E. coli* XL 1-Blue cells. Colonies were grown in 2xYT medium containing ampicillin (100 ug/ml) and 1% glucose at 30° C. until the optical density of 0.5 unit at 600 nm was obtained. Expression of scFv antibody was induced by changing to the medium containing 100 µM IPTG (Sigma-Aldrich) and incubating at 30° C. overnight. The supernatant was separated by centrifugation. After resuspending the pellet in PBS containing 1 mM EDTA and incubating on ice for 10 min, the soluble antibody in the periplasmic fraction was collected by centrifugation. Both supernatant and periplasmic fractions were added to plates coated with anti-idiotype 2E9. After a 2 hour incubation at 37° C., plates were washed and reacted with anti-MycTag antibody (clone 9E10 from ATCC) for 1 hour at 37° C., and subsequently with affinity purified goat anti-mouse antibody (Jackson Immunoresearch) for 1 hour at 37° C. The plates were developed with the substrate o-phenylenediamine (Sigma-Aldrich) as previously described.

Construction of ScFv-Human-1-CH2-CH3 Mouse Human-Chimeric Gene

A single gene encoding scFv8H9 was generated by PCR method using phagemid 8HpHM9F7-1 as the template. Secondary PCR amplification (30 PCR cycles) was carried out to insert the human IgG1 leader sequence at the 5' end of the scFv8H9 DNA plus the restriction sites at the two opposite ends, i.e. Hind III and Not I, at the 5' end of human IgG1 leader and at the 3' end of scFv8H9, respectively. Amplified human IgG1 leader-scFv8H9 DNA was purified by glassmilk beads and digested with Hind III and Not I restriction endonucleases according to manufacturer's instructions. The Hind III-Not I fragment of human IgG1 leader-scFv8H9 cDNA was purified on agarose gel and ligated into pLNCS23 vector carrying the human-γ1-CH2-CH3 gene (kindly provided by Dr. J. Schlom, National Cancer Institute, NIH, Bethesda, Md.)(9). Competent *E. coli* XL 1-Blue cells were transformed with pLNCS23 containing the scFv phagemid. The scFv-CH2-CH3 DNA was amplified with appropriate primers and sequenced using the Automated Nucleotide Sequencing System Model 373 (Applied Biosystems). The sequences agreed with the cDNA sequences of the light and heavy chains of 8H9 as well as the human-γ1-CH2-CH3 (GenBank), including the ASN 297 of the CH2 domain. In this construct, Cys220 of the genetic hinge was replaced by a proline residue, while Cys226 and Cys229 were retained in the functional hinge(9)

Cell Culture and Transfection

CHO cell or NSO myelomas cells (Lonza Biologics PLC, Bershire, UK) were cultured in RPMI 1640 (Gibco-BRL) supplemented with glutamine, penicillin, streptomycin (Sigma-Aldrich) and 10% fetal bovine serum (Gibco-BRL). Using effectene transfection reagent (Qiagen, Valencia, Calif.), recombinant cFv8H9-human-γ1-CH2-CH3 was introduced via the pLNCS23 into CHO cell or NSO myelomas cells. Cells were fed every 3 days, and G418 (1 mg/ml; Gibco-BRL) resistant clones were selected. After subcloning by limiting dilution, chimeric antibodies were produced by high density miniPERM bioreactor from Unisyn Technologies using 0.5% ULG-FBS in Hydridoma-SFM (Invitrogen Corporation, Carlsbad, Calif.). The chimeric antibodies were purified by protein G Pharmacia) affinity chromatography.

SDS-PAGE and Western Blot Analysis

The supernatant, the periplasmic extract and cell extract from the positive clones were separated by reducing and nonreducing SDS-PAGE. 10% SDS-polyacrylamide slab gel and buffers were prepared according to Laemmli.(25) Electrophoresis was performed at 100V for 45 min. After completion of the run, western blot was carried out as described by Towbin.(26)The nitrocellulose membrane was blocked by 5% nonfat milk in TBS solution for 1 hour and incubated with anti-idiotype 2E9 antibody overnight at 4° C. After incubating with HRP-conjugated goat anti-rat Ig (Fisher Scientific Co., Pittsburgh, Pa.), the signal was detected by ECL system (Amersham-Pharmacia Biotech).

Cytotoxicity Assay

Target NMB7 or HTB-82 tumor cells were labeled with $Na_2{}^{51}CrO_4$ (Amersham Pharmacia) at 100 uCi/10^6 cells at 37° C. for 1 hour. After the cells were washed, loosely bound ^{51}Cr was leaked for 1 hour at 37° C. After further washing, 5000 target cells/well were admixed with lymphocytes to a final volume of 200 µl/well. Antibody dependent cell-mediated cytotoxicity (ADCC) was assayed in the presence of increasing concentrations of chimeric antibody. In complement mediated cytotoxicity (CMC), human serum as source of complement (at 1:40, 1:80, 1:160, 1:320, 1:640 dilution) was used instead of lymphocytes. The plates were incubated at 37° C. for 4 hours. Supernatant was harvested using harvesting frames (Skatron, Lier, Norway). The released ^{51}Cr in the supernatant was counted in a universal gamma-counter (Packard Bioscience, Meriden, Conn.). Percentage of specific release was calculated using the formula 100%×(experimental cpm−background cpm)/(10% SDS releasable cpm−background cpm), where cpm were counts per minute of ^{51}Cr released. Total release was assessed by lysis with 10% SDS (Sigma-Aldrich), and background release was measured in the absence of cells. The background was usually <30% of total for either NMB7 or HTB-82 cells. Antibody 3F8 was used as the positive control.(27)

Iodination

MoAb was reacted for 5 min with ^{125}I (NEN Life Sciences, Boston, Mass.) and chloramine T (1 mg/ml in 0.3M Phosphate buffer, pH 7.2) at room temperature. The reaction was terminated by adding sodium metabisulfite (1 mg/ml in 0.3M Phosphate buffer, pH 7.2) for 2 min. Free iodine was removed with A1GX8 resin (BioRad, Richmond, Calif.) saturated with 1% HSA (New York Blood Center Inc., New York, N.Y.) in PBS, pH 7.4. Radioactive peak was collected and radioactivity (mCi/ml) was measured using a radioisotope calibrator (Squibb, Princeton, N.J.). Iodine incorporation and specific activities were calculated. Trichloroacetic acid (TCA) (Fisher Scientific) precipitable activity was generally >90%.

In Vitro Immunoreactivity of Iodinated Antibody

Immunoreactivity of radioiodine labeled antibody was assayed using purified anti-idiotype antibody 2E9 as the antigen. Appropriate dilutions of ^{125}I labeled antibodies were added to plates in duplicates, and then transferred to freshly prepared antigen plates after 1 h and 4 h of binding at 4° C., respectively. The final binding step was allowed to proceed overnight at 4° C. The total percent radioactivity bound was a summation of 3 time points for each antibody dilution. For native 8H9, maximum immunoreactivity averaged ~65%, while 8H9 scFv-Fc (ch8H9) antibody was ~48%.

Animal Studies

Athymic nude mice (nu/nu) were purchased from NCI, Frederick M D. They were xenografted subcutaneously with LAN-1 neuroblastoma cell line (2x10^6 cells/mouse) suspended in 100 μl of Matrigel (Beckton-Dickinson Bio-Sciences, Bedford, Mass.) on the flank. After 3 weeks, mice bearing tumors of 1-1.5 cm in longest dimension were selected. Animals were injected intravenously (retrorbital plexus) with 20 μCi of ^{125}I labeled antibody. They were anesthesized with ketamine (Fort Dodge Animal Health, Fort Dodge, Pa.) intraperitoneally and imaged at various time intervals with a gamma camera (ADAC, Milpitas, Calif.) equipped with grid collimators. Serial blood samples were collected at 5 min, 1, 2, 4, 8, 18, 24, 48, 72, 120 h from mice injected with 10-11 uCi ^{125}I labeled antibody. Groups of mice were sacrificed at 24 h, 48 h, and 120 h and samples of blood (cardiac sampling), heart, lung, liver, kidney, spleen, stomach, adrenal, small bowel, large bowel, spine, femur, muscle, skin, brain and tumor were weighed and radioactivity measured by a gamma counter. Results were expressed as percent injected dose per gram. Animal experiments were carried out under an IACUC approved protocol, and institutional guidelines for the proper and humane use of animals in research were followed.

Results

Anti-8H9-Idiotypic Antibodies

Rat hybridomas specific for 8H9 and nonreactive with control murine IgG1 were selected. After subcloning by limiting dilution, rat antibodies were produced by bulk culture in roller bottles and purified by protein G affinity column. By ELISA, 2E9, 1E12, and 1F11, all of rat subclass IgG2a, were specific for 8H9, while nonreactive with a large panel of purified monoclonal antibodies (Table 1). In contrast, the antibodies 3C2, 4C2 5C7, 7D6 and 8E12 from the same fusions were not specific for 8H9. The rest of the experiments in this study was carried out using antibody 2E9 because of its high titer in vitro. 2E9 specifically inhibited the binding of 8H9 to LAN-1 neuroblastoma (FIG. **1**A) and HTB82 rhabdomyosarcoma (FIG. **1**B) while control rat IgG1 (A1G4) had no effect (FIG. **1**C).

Construction and Expression of 8H9 ScFv

After three rounds of panning of the recombinant phagemid on the anti-idiotypic antibody 2E9, the eluted phage was used to infect *E. coli* HB2151 cells and scFv expression was induced by IPTG. ScFv from periplasmic soluble protein fraction was tested for binding to 2E9 on ELISA. Three 8H9 scFv clones when compared with the MoAb 8H9 showed similar titers. The clone 8HpHM9F7-1 was selected for subcloning. The DNA sequence of 8HpHM9F7-1 agreed with those of the 8H9VH and 8H9VL.

The supernatant, periplasmic soluble and cells pellet lysates of 8HpHM9F7-1 were separated by nonreducing SDS-PAGE, and analyzed by western blotting. A protein band with molecular weight of 31 KD was found in the supernatant, the periplasmic and cell pellet extracts using anti-MycTag antibody which recognized the sequence GAPVPDPLEPR (SEQ ID NO. 18). No such band was detected in control cells or 8HpHM9F7-1 cells without IPTG treatment.

Construction of Chimeric Mouse scFv-Human Fc

Chimeric clones from CHO and NSO were screened by ELISA binding on 2E9. Clone 105 from NSO and clone 1G1 from CHO were chosen for scale-up production. By SDS-PAGE and by western blot analysis, a single chain of 54 kD under reducing conditions, and a homodimer of 102 kD under nonreducing conditions were found (FIG. **2**). Antigen specificity was demonstrated by its binding to tumor cells. In FIG. **3**, mean fluorescence plateaued around 3-5 ug/mL of both ch8H9 and 8H9 for both HTB-rhabdomyosarcoma and LAN-1 neuroblastoma cells, while negative (<10% mean fluorescence) for the control cell line Daudi (data not shown). Cell staining (5 ug/ml of ch8H9) was completely inhibited by 1 ug/ml of anti-idiotypic antibody 2E9 on FACS analysis (data not shown). DNA sequencing confirmed the presence of 8H9scFv and the CH2-CH3 domain of human Fcγ1.

In Vitro and In Vivo Properties of ch8H9

The ch8H9 antibody mediated ADCC in the presence of human lymphocytes with a 16% maximum cytotoxicity at 50:1 E:T ratio, significantly higher than the controls 3F8 or 8H9 (FIG. **4**A). However, it was unable to mediate CMC in the presence of human complement (data not shown). In biodistribution studies, it localized well to HTB82 and LAN-1 xenografts (FIG. **5**). Blood clearance studies showed that chimeric 8H9 (102 kD MW) had T-½ of 5.3 h, and T-½ of 43 h when compared to averages of 4.5 h and 71 h, respectively, for native 8H9 (160 kD MW), a result of the smaller molecular size of the construct (FIG. **6**). Similarly, although the percent injected dose per gram of the chimeric construct (Table 2) was lower for all tissues (average of 44% at 48 h, and 75% at 120 h), the tumor-non tumor ratios (Table 3) were similar to those of native 8H9 (98% at 48 h and 85% at 120 h).

Discussion

We demonstrated that by using rat anti-idiotypic antibody as antigen surrogate, scFv and scFv-fusion proteins can be conveniently produced. As proof of principle we utilized the anti-idiotypic antibody to clone scFv from the murine hybridoma cDNA library. The anti-idiotypic antibody was then used to select for scFv-Fc chimeric antibodies. Both the scFv and scFv-Fc fusion protein derived by our method were specific for the natural antigen, comparable to the native antibody 8H9.

While scFv provides the building block for scFv-fusion proteins, it is not the ideal targeting agent by itself. Being a small protein, its clearance is rapid. Moreover, it is often retained by the kidney, delivering undesirable side effects if the scFv construct is cytotoxic. Since avidity is a key parameter in tumor targeting in vivo, its biggest limitation is its uni-valency and often suboptimal affinity for the antigen. By using VH-VL linkers of decreasing length, spontaneous dimeric, trimeric and polymeric scFv have been produced. However, these oligomers are not bonded by covalent linkage, and may dissociate in vivo. An alternative approach is to take advantage of the human Fc, which has the natural ability to homodimerize through disulfide-bonds, thereby allowing the juxtaposition of two binding domains. Fc functions such as CMC and ADCC could also be achieved.(9,28-31)

Unlike standard 2-chain chimeric antibodies, only one polypeptide is needed for the scFv-Fc chimeric; unbalanced synthesis of heavy and light chains is not an issue. Larger dimeric fragments are also likely to have increased serum-half life compared to scFv and thus improved tumor targeting.(32,33) Homodimerization of tumor cell-surface antigens by soluble antibody may also trigger apoptosis of tumor cells.(34) No less important is the availability of validated purification techniques using protein A or protein G through their binding to the Fc portion.(31) Tetravalent scFv (monospecific or bispecific) are natural extensions of the diabody approach to scFv-Fc fusion strategy,(13,15) where a significant increase in avidity can be achieved. More recently, scFv-streptavidin fusion protein has been produced for pretargeted lymphoma therapy.(35) Here scFv-streptavidin forms natural tetramers, to which biotinyated ligands can bind with high affinity.

Anti-idiotypic antibodies have greatly facilitated clone selection in the construction of soluble scFv-fusion proteins or cell bound surface scFv. We have successfully applied similar technology to anti-GD2 monoclonal antibodies.(36) Being immunoglobulins, their structure, stability, biochemistry, are generally known. Unlike natural antigens where each individual system has its unique and difficult to predict properties. As surrogate antigens, anti-idiotypic antibodies are ideal for standardization and quality control, especially for initial clinical investigations where the nature of the antigen is not fully understood. Potential limitations exist for the anti-idiotype approach. Only those anti-ids (Ab2) that recognize the antigen-binding site of the immunizing MoAb can mimic the original antigen. A reliable test for Ab2 is its ability to induce an antigen-specific immune response. Alternatively, antigen specificity of the scFv selected by the anti-idiotype must be validated by binding to cells or membrane preparations.

Once validated, the anti-idiotype can be used as antigen surrogate for cloning and assay of other scFv-fusion proteins. Although our scFv-Fc fusion protein ch8H9 mediated ADCC, it could not mediate CMC. This finding differs from previous scFv-Fc fusion proteins.(9,30,31) It is possible that the affinity of the antibody 8H9 may be suboptimal to mediate efficient ADCC/CMC; or that the p58 antigen and tumor lines used may not be optimal targets for CMC. Alternatively, poor in vitro Fc function may relate to the oligosaccharide structures in the Fc region.(37) In normal IgG, these oligosaccharides are generally of complex biantennary type, with low levels of terminal sialic acid and bisecting N-acetylglucosamine (GlcNAc), the latter being critical for ADCC. ADCC function is often inefficient among chimeric antibodies expressed in cell lines which lack the enzyme (1,4)-N-acetylglucosaminyltransferase III (GnIII),(38) that catalyzes the formation of bissecting oligosaccharides. This enzyme can be transfected into producer lines to increase the level of bisecting GlcNAc and to increase the ADCC function of secreted chimeric antibodies.(38) It is also possible that the absence of the CH1 domain in the Fc may modify the accessability of the ASN297 residue to glycosyltransferases in some scFv-Fc constructs such as ours.(37) On the other hand, an scFv-Fc that lacks binding to Fc receptor may have less nonspecific binding to white cells, thereby decreasing blood pooling in targeted therapy. These findings may have implications in scFv-Fc strategies to improve effector functions.

TABLE 1

Anti-8H9-idiotypic antibodies: Specificity by ELISA

		1E12	1F11	3C2	4C2	5C7	7D6	8E12	2E9
MoAb	Class	2a	2a	2b	μ	μ	1	μ	2a
MOPC-315	a	–	–	+++	–	–	–	–	–
20.4	1	–	–	+++	+++	++	+++	–	–
2C9	1	–	–	+++	+++	+++	+++	++	–
2E10	1	–	–	+++	–	–	+	–	–
3E6	1	–	–	+++	+++	+++	+++	+++	–
3E7	1	–	–	+++	–	–	+	–	–
4B6	1	–	–	+++	+++	++	+++	–	–
5F9	1	–	–	+++	+++	+++	+++	+	–
8H9	1	+++	++	+++	+++	++	+++	–	++
MOPC-21	1	–	–	+++	+++	+++	+++	–	–
UJ 13A	1	–	–	+++	++	+	–	–	–
3A5	2a	–	–	+++	–	–	–	–	–
MOPC-1	2a	–	–	+++	+	–	–	–	–
3F8	3	–	–	+++	–	–	–	–	–
FLOPC-21	3	–	–	+++	++	–	++	–	–
NRCO-04	3	–	–	+++	–	–	–	–	–
R24	3	–	–	+++	–	–	–	–	–
TIB114	3	–	–	+++	+	–	++	–	–
Y5606	3	–	–	+++	–	–	–	–	–
3A7	μ	–	–	+	–	–	–	–	–
3G6	μ	–	–	+++	–	–	–	–	–
5F11	μ	–	–	+	–	–	–	–	–
K9	μ	–	–	+++	–	–	–	–	–
MOPC-104E	μ	–	–	+++	–	–	–	–	–

Note:

OD < 0.5 = –, 0.5~1 = +, 1~2 = ++, >2 = +++

TABLE 2

Percent Injected Dose per gram over time in hours

	Percent injected dose/gm over time (h) mean +/− se				
	Chimeric			Native	
Organs	24	48	120	48	120
Skin	1.4 +/− 0.2	0.2 +/− 0.1	0.7 +/− 0.0	0.2 +/− 0.0	1.8 +/− 0.2
Heart	1.3 +/− 0.2	0.2 +/− 0.1	0.9 +/− 0.0	0.4 +/− 0.2	2.6 +/− 0.2
Lung	2.9 +/− 0.4	0.4 +/− 0.3	1.9 +/− 0.1	0.5 +/− 0.3	4.0 +/− 0.3
Liver	1.2 +/− 0.1	0.1 +/− 0.1	0.8 +/− 0.0	0.2 +/− 0.2	1.4 +/− 0.2
Spleen	0.9 +/− 0.2	0.2 +/− 0.0	0.5 +/− 0.1	0.2 +/− 0.2	1.4 +/− 0.1
Kidney	1.5 +/− 0.1	0.1 +/− 0.1	0.9 +/− 0.2	0.5 +/− 0.1	1.9 +/− 0.1
Adrenal	0.9 +/− 0.1	0.1 +/− 0.2	0.5 +/− 0.2	0.5 +/− 0.5	1.8 +/− 0.0
Stomach	1.3 +/− 0.3	0.3 +/− 0.1	0.6 +/− 0.1	0.3 +/− 0.1	1.3 +/− 0.3
Samll intestine	0.6 +/− 0.1	0.1 +/− 0.0	0.3 +/− 0.1	0.2 +/− 0.0	0.7 +/− 0.1
Large intestine	0.6 +/− 0.1	0.1 +/− 0.0	0.3 +/− 0.1	0.2 +/− 0.1	0.6 +/− 0.0
Bladder	1.2 +/− 0.1	0.1 +/− 0.2	0.6 +/− 0.2	0.4 +/− 0.2	1.0 +/− 0.2
Muscle	0.5 +/− 0.1	0.1 +/− 0.0	0.3 +/− 0.1	0.2 +/− 0.0	0.5 +/− 0.1
Femur	0.6 +/− 0.1	0.1 +/− 0.0	0.3 +/− 0.1	0.2 +/− 0.1	0.8 +/− 0.0
Spine	0.6 +/− 0.1	0.1 +/− 0.0	0.4 +/− 0.1	0.2 +/− 0.1	0.8 +/− 0.1
Tumor	4.0 +/− 0.3	0.3 +/− 0.5	3.6 +/− 0.4	2.1 +/− 1.3	9.4 +/− 0.5
Brain	0.2 +/− 0.0	0.0 +/− 0.0	0.1 +/− 0.0	0.1 +/− 0.0	0.2 +/− 0.0
Blood	5.3 +/− 0.3	0.3 +/− 0.3	3.1 +/− 0.2	1.2 +/− 0.7	8.3 +/− 0.8

TABLE 3

Tumor to normal tissue over time in hours

	Tumor to normal tissue ratio over time (h), mean +/− se				
	Chimeric			Native	
Organs	24	48	120	48	120
Skin	3.0 +/− 0.3	6.0 +/− 1.3	10.7 +/− 1.7	5.2 +/− 0.7	7.2 +/− 2.2
Heart	3.3 +/− 0.7	4.0 +/− 0.7	5.6 +/− 0.4	3.6 +/− 0.3	7.7 +/− 2.9
Lung	1.6 +/− 0.4	2.2 +/− 0.5	4.5 +/− 0.7	2.3 +/− 0.3	5.0 +/− 1.7
Liver	3.5 +/− 0.5	5.2 +/− 1.3	8.7 +/− 1.1	6.5 +/− 0.4	0.1 +/− 3.4
Spleen	5.1 +/− 1.0	8.1 +/− 1.6	12.8 +/− 3.4	6.7 +/− 0.4	15.1 +/− 5.7
Kidney	2.8 +/− 0.3	4.3 +/− 1.1	5.9 +/− 1.6	5.1 +/− 1.0	8.9 +/− 1.1
Adrenal	4.8 +/− 0.5	8.7 +/− 2.3	10.0 +/− 3.2	5.8 +/− 1.3	11.6 +/− 1.6
Stomach	3.6 +/− 0.8	6.7 +/− 1.3	13.8 +/− 4.2	7.5 +/− 1.7	14.5 +/− 4.3
Samll intestine	6.6 +/− 0.7	11.8 +/− 2.1	16.0 +/− 3.7	13.3 +/− 2.2	21.7 +/− 6.1
Large intestine	7.1 +/− 1.0	12.7 +/− 2.2	25.9 +/− 7.1	15.7 +/− 3.4	28.5 +/− 8.9
Bladder	3.5 +/− 0.3	14.3 +/− 9.2	10.2 +/− 3.3	12.4 +/− 5.5	12.3 +/− 5.3
Muscle	7.9 +/− 0.7	13.6 +/− 2.4	21.3 +/− 6.8	18.2 +/− 1.3	26.8 +/− 9.6
Femur	6.7 +/− 1.1	11.8 +/− 2.4	20.5 +/− 6.8	11.8 +/− 1.3	27.9 +/− 6.5
Spine	6.7 +/− 0.9	6.8 +/− 1.9	14.2 +/− 3.7	11.1 +/− 1.1	19.6 +/− 6.2
Tumor	1.0 +/− 0.0	1.0 +/− 0.0	1.0 +/− 0.0	1.0 +/− 0.0	1.0 +/− 0.0
Brain	22.7 +/− 2.9	40.9 +/− 8.6	38.7 +/− 10.4	44.6 +/− 10.4	68.2 +/− 35.2
Blood	0.8 +/− 0.1	1.2 +/− 0.2	1.8 +/− 0.3	1.1 +/− 0.1	2.3 +/− 0.8

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Second Series of Experiments

Anti-Idiotypic Antibody Facilitates scFv Chimeric Immune Receptor Gene Transduction and Clonal Expansion of Human Lymphocytes for Tumor Therapy

Experimental Details

Chimeric immune receptors (CIR) transduced into lymphocytes link target recognition by single chain antibody Fv (scFv) to activation through CD28/TCRζ signaling. As surrogate antigens, anti-idiotypic antibodies may facilitate gene-transduction and clonal expansion of human lymphocytes for in vivo tumor therapy. The murine monoclonal antibody (MoAb) 8H9 reacts with a novel antigen widely expressed on solid tumors (Cancer Res 61:4048, 2001). A CIR consisting of human CD8-leader sequence, 8H9scFv, CD28 (transmembrane and cytoplasmic domains), and TCR-ζ chain was constructed, ligated into the pMSCVneo vector, and used to transfect the packaging line GP+envAM12 bearing an amphotropic envelope. Rat anti-idiotypic MoAb 2E9 (IgG2a) was used to clone retroviral producer line as well as to expand gene-modified primary human lymphocytes. Sequential enrichments using either affinity chromatography or cell sorting using anti-idiotypic MoAb 2E9 significantly improved the percentage of producer clones positive for surface 8H9-scFv and the efficiency of their supernatant in transducing the indicator cell line K562. By three weeks of in vitro culture, >95% of transduced primary human lymphocytes were CIR-positive. Upon periodic stimulation with 2E9, these lymphocytes underwent >10^6 fold expansion by 6 months in culture. They mediated antigen-specific non-MHC restricted cytokine release and tumor cytotoxicity. When admixed with tumor cells or injected intravenously, they inhibited human xenograft growth in SCID mice. Anti-idiotypic antibody may provide a useful tool for optimizing gene transduction of CIR fusion constructs into primary human lymphocytes and their continual expansion in vitro.

Adoptive cell therapy using ex vivo expanded tumor-selective T-cells can effect dramatic remissions of virally induced malignancies, a process critically dependent on clonal frequency, where rapid exponential expansion of specific cytolytic T-lymphocytes (CTL) is required. (Papadopoulos, 1994 #2140; Heslop, 1997 #4703) T-cells proliferate when activated (e.g. anti-CD3). However, apoptosis occurs unless a costimulatory signal (e.g. anti-CD28) is present. (Daniel, 1997 #4714) However, human tumor targets often lack costimulatory molecules (e.g. CD80), or overstimulate inhibitory receptors (e.g. CTL4) such that the CD28 pathway is derailed. In addition, many tumors downregulate major histocompatibility complex (MHC) molecules to escape engagement by the T-cell receptor (TCR). Through genetic engineering, chimeric immune receptors (CIR) linking tumor-selective scFv to T-cell signal transduction molecules (e.g. TCR-ζ chain and CD28) will activate lymphocytes following tumor recognition, triggering the production of cytokines and tumor lysis. (Eshhar, 1993 #6028; Stancovski, 1993 #2392; Moritz, 1994 #3399; Wels, 1995 #2452; Hwu, 1993 #2394; Eshhar, 2001 #5665; Rossig, 2001 #6088; Ma, 2002 #6437) T-cell can also be genetically engineered to secrete cytotoxic cytokines, (Rosenberg, 1995 #2372) toxins, (Yang, 1997 #3395) or to metabolize prodrugs. (Culver, 1992 #3478; Wei, 1994 #3466) However, significant technologic gaps remain: (1) Gene transduction into primary human lymphocytes is inefficient, (2) Antigen specific T-cells cannot be easily enriched and expanded, (3) Optimal T-cell activation may require multiple signals, and (4) Demonstration of anti-tumor effect of these human T-cells in established tumor models has been difficult and so far unsuccessful in patients. (Ma, 2002 #6437) Furthermore, although CIR redirected T-cells can recycle their lytic activity, (Weijtens, 1996 #3396) a costimulatory signal, either through CD28 or 4-1BB engagement, may help reduce activation-induced apoptotic death. (Maus, 2002 #6438) CIR with multidomains was recently described, where the intracellular domain of CD28 was ligated to the 5' end of TCR-ζ chain and introduced into Jurkat cells, with the expected "two signals" when scFv was triggered by tumor cells. (Finney, 1998 #4574) IL-2 production was 20 times more than CIR with ζ-chain only. Primary mouse CD8+ T lymphocytes expressing the scFv-CD28-ζ receptor secreted Tc1 cytokines, induced T-cell proliferation, and inhibited established tumor growth and metastasis in vivo, a process shown to be critically dependent on IFN-γ secretion. (Haynes, 2002 #6477) CD28-mediated cytokine secretion through CIR activation was recently demonstrated in primary human T-cells. (Krause, 1998 #3956; Maher, 2002 #6433)

To monitor scFv gene expression, anti-linker antibody may be useful. However, its efficiency depends on the accessibility of the scFv-linker portion. Although purified antigens can also be used to monitor scFv expression, certain classes (complex carbohydrates or unstable antigens) can be difficult to prepare and their chemistry highly variable. Without a standardized reagent for affinity purification or enrichment of virus producer cells, as well as monitoring and sorting of transduced lymphocytes, CIR technology remains inefficient. A dicistronic construct consisting of scFv-CD28-γ and green fluorescent protein (GFP) exploited the latter was to monitor gene transduction and to enrich producer lines. (Eshhar, 2001 #5665) Although GFP can validate the gene transfer process, its added immunogenicity and its safety in clinical applications remain uncertain.

Anti-idiotypic antibodies are frequently used as antigen-mimics for infectious diseases and cancer. Thanavala, 1986 #3290; Wagner, 1997 #6019) Internal image rat anti-idiotypic antibodies can be conveniently produced against mouse MoAb. Since large scale production of clinical grade MoAb is now routine, anti-idiotypic antibodies may be ideal surrogates especially if the antigen is not readily available. In addition, the biochemistry of immunoglobulins in positive selection (panning, affinity chromatography, sorting) and binding assays is well-known and is easy to standardize. Single chain antibody fragments with specificity for cell surface antigens were successfully isolated by phage display utilizing internal image anti-idiotypic antibodies. (Hombach, 1998 #6363) We recently described a novel tumor antigen reactive with a murine MoAb 8H9. (Modak, 2001 #3872) The antigen was difficult to purify given its lability and glycosylation. Here we demonstrate that an anti-idiotypic MoAb against 8H9 can be used as a surrogate antigen for cloning CIR into primary human lymphocytes, i.e. a CIR of 8H9scFv, human CD28 and human TCR-ζ chain. While previous studies showed that anti-idiotypic antibody can enhance cytotoxicity of scFv-γR-gene modified murine cytotoxic T-cell line, (Reinhold, 1999 #4340) we now show that anti-idiotypic MoAb, besides allowing rapid affinity enrichment of producer cell line and monitoring of surface scFv expression, induces clonal expansion of CIR-modified primary human lymphocytes. Highly cytotoxic lymphocytes can be propagated in vitro undergoing 10^6 fold expansion over a period of 6 months.

Materials and Methods

Materials Cells were cultured in RPMI 1640 with 10% newborn calf serum Hyclone, Logan, Utah) supplemented with 2 mM glutamine, 100 U/ml of penicillin and 100 ug/ml of streptomycin. 8H9 murine IgG1 monoclonal antibody directed at gp58 on human solid tumors has been previously described. (Modak, 2001 #3872) Anti-idiotypic antibodies were produced from LOU/CN rats. (Cheung, 1993 #1499) Clones (2E9, 1E12, 1F11) were selected based on selective binding to 8H9 antibody and not to other myelomas. After repeated subcloning, 2E9 (rat IgG2a) was chosen for its high in vitro antibody production using high density miniPERM bioreactor (Unisyn technologies, Hopkinton, Mass.), and purified by protein G affinity chromatography (Hitrap G, Amersham-Pharmacia, Piscataway, N.J.). The IgG fraction was eluted with pH 2.7 glycine-HCl buffer and neutralized with 1 M Tris buffer pH 9. After dialysis in PBS at 4° C. for 18 hours, the purified antibody was filtered through a 0.2 um Millipore filter (Millipore Inc. Bedford Mass.), and stored frozen at −70° C. Purity was determined by SDS-PAGE electrophoresis using 7.5% acrylamide gel. ELISA was used to detect rat anti-idiotypic antibodies (Ab2) as previously described. (Cheung, 1993 #1499) Rat IgG1 anti-5F11 anti-idiotypic MoAb 1G8 was similarly produced.

Construction of ScFv Gene scFv was constructed from 8H9 hybridoma cDNA by recombinant phage display (Amersham-Pharmacia). Amplified ScFv DNA, purified by glassmilk beads, restriction digested (Sfi I and Not I), and inserted into the pHEN1 vector (kindly provided by Dr. G. Winter, Medical Research Council Centre, Carmbridge, UK). Competent *E. Coli* XL-1 Blue cells (Stratagene, La Jolla, Calif.) were transformed with the pHEN1 phagemid. Following rescue with the helper phage M13 KO7 (Pharmacia), recombinant phagemids were enriched by panning. 50 ul of anti-8H9 idiotypic antibody 2E9 (50 ug/ml) in PBS were coated on the 96-well polyvinyl microtiter plates and incubated at 37° C. for 1 hour. 100 ul of the supernatant from phage library were added to each well and incubated for 2 hours. The plate was washed 10 times with PBS containing 0.05% BSA. Antigen-positive recombinant phage captured by anti-idiotypic MoAb 2E9 was eluted with 0.1M HCl (pH 2.2 with solid glycine and 0.1% BSA) and neutralized with 2M Tris solution. This panning procedure was repeated three times. The phagemid 8HpHM9F7-1 was chosen for the rest of the experiments. The appropriate size scFv (31 kD) was demonstrated in the supernatant, periplasmic and cell extracts by nonreducing SDS-PAGE and western blotting. (Towbin, 1979 #6020) using anti-Myc Tag antibody (clone 9E10 from ATCC, Rockville, Bethesda, Md.).

ELISA The selected phage was used to reinfect *E. coli* XL-1 Blue cells. Colonies were grown in 2xYT medium containing ampicillin (100 ug/ml) and 1% glucose at 30° C. until the optical density at 600 nm of 0.5 was obtained, and expression of scFv antibody was induced with 100 uM IPTG (Sigma-Aldrich) at 30° C. overnight. Both supernatant and periplasmic fractions were assayed for scFv on anti-idiotype 2E9 coated plates. After incubating 2 hours at 37° C., plates were washed and reacted with anti-MycTag antibody for 1 hour at 37° C. After washing, affinity purified goat anti-mouse antibody (Jackson Immunoresearch, West Grove, Pa.) was allowed to react for 1 hour at 37° C. and the plates were developed with the substrate o-phenylenediamine (Sigma-Aldrich).

Construction of sc8H9-hCD28$_{TM}$-hCD28$_{cyto}$-hTCRζ-pMSCVneo Using the assembled gene sequences, secondary PCR amplifications using synthetic oligodeoxynucleotide primers (see below) were performed. Briefly, a 541 reaction mixture containing 200 μM of each deoxynucleotide triphosphate, 0.2 μM of each primer, 2 units of AmpliTag Gold DNA polymerase (Applied Biosystems, Foster City, Calif.), and 50 ng of template DNA was subjected to a 10 min denaturation and activation step at 95° C., followed by 30 cycles of denaturation (1 min at 95° C.), annealing (2 min at 55° C.), and extension (2 min at 72° C.). This was followed by a final extension for 8 min at 72° C. Each of the amplified products was purified with Geneclean Kit (Bio 101, Vista, Calif.).

Synthetic Oligodeoxynucleotide Primers for DNA Amplification

(1) hCD8a leader-scFv-CD28:

(SEQ ID NO. 1)
Sense Primer (Hpa I-Human CD8a Leader)
5'-TTA TTA CGA GTT/AAC ATG GCC TTA CCA GTG ACC-3'

(SEQ ID NO. 2)
Antisense Primer (Xho I-Human CD28)
5'-CTT GGT C/TCGAG TGT CAG GAG CGA TAG GCT GC-3'

(2) 8H9scFv:

(SEQ ID NO. 3)
Sense Primer (Cla I-8H9 heavy chain)
5'-TTA TTA CGA AT/CGAT T GCC CAG GTC AAA CTG-3'

(SEQ ID NO. 4)
Antisense Primer (Not I- 8H9 light chain)
5'-CTT GGT G/CGGCCGC CTG TTT CAG CTC CAG-3'

(3) 5F11scFv:

(SEQ ID NO. 5)
Sense Primer (Cla I-5F11 heavy chain)
5'-TTA TTA CGA AT/CGAT TCA GCA GTC AGG ACC-3'

(SEQ ID NO. 6)
Antisense Primer (Not I-5F11 light chain)
5'-CTT GGT G/CG GCC GC CCG TTT TAT TTC CAA CTG-3'

(4) hTCR-ζ chain:

(SEQ ID NO. 7)
Sense primer (Bst U I- CD28 end-Xho I-hTCRζ [cytoplasmic domain])
5'- CG/C GAC TTA GCA GCC TAT CGC TCC TGg CAC/TCG

AGa AGA GTG AAG TTC-3'

Antisense Primer (BglII-hTCR z)
(SEQ ID NO. 8)
5'-CTT GGT A/GA TCT TCA GCG AGG GGG CAG GGC-3'

Templates for DNA Amplification and Construction The single gene encoding hCD8a-leader-sc3G6-CD28 was previously described. (Krause, 1998 #3956) Its cDNA was generated by PCR using the Hpa I, Xho I fragment of hCD8a-leader-scFv-CD28 cDNA, and ligated into pMSCVneo vector (Clontech, Palo Alto, Calif.). ScFv-8H9 was amplified from the 8HpHM9F7-1 phagemid, and the excised 8H9 scFv gene swapped into the hCD8a-leader-scFv3G6-CD28 cassette of pMSCVneo using the Cla I-Not I restriction enzymes. Human TCR-ζ chain was amplified from the plasmid pcDNA3.1/VJABLZH (kindly provided by Dr. Ira Bergman, University of Pittsburgh, Pa.), and ligated downstream of CD28 gene, using Xho I and Bgl II restriction sites. Using the method supplied by manufacturer (Stratagene), competent *E. Coli* XL-1 Blue cells were transformed with the vector pMSCVneo containing the insert. All gene constructs were checked by DNA sequencing.

Cell Culture and Transfection The amphotropic packaging cell line GP+envAM12 (Genetix Pharmaceuticals, Cambridge, Mass.) and all retroviral producer lines were maintained in Dulbecco's modified Eagle's medium (Gibco-BRL, Gaithersburg, Md.) supplemented with glutamine, penicillin, streptomycin (Gibco-BRL), and 10% fetal bovine serum (Gibco-BRL). Using Effectene Reagent (Qiagen, Valencia, Calif.), vector DNA was transfected into GP+envAM12 packaging cells and selected with G418 (400 ug/ml; Gibco-BRL).

Enrichment and Cloning of Packing Lines by Affinity Column The retroviral producer lines were affinity enriched using MACS goat anti-rat IgG MicroBeads on the Mini-MACS system (Miltenyi, Auburn, Calif.). In brief, the transduced packing lines were reacted with 2E9 (10 ug per 10^6 packing cells) on ice for 30 minutes, washed, applied to the anti-rat column, and eluted according to manufacturer's protocol. Cloning was done by limiting dilution. scFv expression on producer clones were monitored by flow cytometry (FACSCalibur, Becton Dickinson Immunocytometry Systems, San Jose, Calif.) using anti-idiotypic antibodies 2E9 or 1E12. Virus-containing supernatant was used to infect K562 cells, and gene transduction was measured by scFv surface expression.

Enrichment and Cloning of Packing Lines by FACS sorting Cell sorting was carried out using a Cytomation MoFlo digital cell sorter (Cytomation Inc., Fort Collins, Colo.), selecting for the brightest (0.1%) 2E9-reactive cells, and seeded into 96-well plates at 10 cells per well.

Peripheral Blood Mononuclear Cells (PBMC) Peripheral blood from normal volunteers and patients were obtained aseptically with informed consent according to the guidelines of the Institutional Review Board of Memorial Sloan-Kettering Cancer Center. PBMC were isolated by centrifugation on Ficoll (density, 1.077 g/ml) for 30 min at 25° C. and washed twice with PBS. PBMC (10^6/ml) were cultured in RPMI 1640 supplemented with 10% human AB serum (Gemini Bio-Products, Woodland, Calif.), 50 μM 2-mercaptoethanol, 2 μM L-glutamine, and 1% penicillin-streptomycin (Gibco-BRL), and activated with solid phase anti-CD3 (1 μg/ml; clone OKT3; PharMingen, San Diego, Calif.) and anti-CD28 (1 ug/ml; clone CD28.2; PharMingen) MoAbs for 3 days at 37° C. before retroviral transfection. (Koehne, 2000 #5893)

Retroviral Transduction Protocol PBMC or K562 were suspended at 1-5x10^5 cells/ml of freshly harvested supernatant from retroviral producer cells, containing 8-10 ug/ml hexadimethrine bromide (polybrene, Sigma-Aldrich), centrifuged at 1000×g at room temperature for 60 minutes, before culturing in 12-well tissue plates overnight. The viral supernatant was then aspirated and fresh IMDM (Gibco-BRL) medium containing 100 U/ml of IL2 and changed approximately every 5 days to maintain a cell count between 1-2×10^6 cells/ml. (Koehne, 2000 #5893) Transfected cells were cultured in wells coated with anti-idiotypic antibody 2E9, for 2 consecutive days each from weeks 3 to 7, and then transferred to plates freshly coated with 2E9 at every 3 weeks intervals.

Real-Time Quantitative PCR Real-time quantitative PCR for scFv gene copy number and RT-PCR for mRNA were performed on cryopreserved lymphocyte samples using ABI Prism 7700 Sequence Detection System (Applied Biosystems, Foster City, Calif.) as previously described. (Mora, 2001 #6436; Cheung, 2001 #5733) β-actin was the endogenous control for DNA, whereas glyceraldehyde-3-phosphate dehydrogenase (GAPDH) for mRNA. Primers and probe for scFv were designed using the Applications-based primer design software Primer Express (Applied Biosystems, ABI). The primers and probes for β-actin and GAPDH were from ABI.

8H9scFv
sense primer: (SEQ ID NO. 9)
5'- CAAATATGCTTCCCAATCCATCT-3'

antisense primer: (SEQ ID NO. 10)
5'- ACTGAGAGTGAAATCTGACCCTGAT-3'

Probe: (SEQ ID NO. 11)
FAM-5'-TCCCCTCCAGGTTCAGTGGCAGTG-3'-TAMRA

β-actin
sense primer: (SEQ ID NO. 12)
5'- TCACCCACACTGTGCCCATCTACGA-3'

antisense primer: (SEQ ID NO. 13)
5'- CAGCGGACCCGCTCATTGCCAATGG-3'

Probe: (SEQ ID NO. 14)
FAM-5'-ATGCCC-TAMRA-CCCCCATGCCATCCTGCGTp-3'

GAPDH
sense primer: (SEQ ID NO. 15)
5'-GAAGGTGAAGGTCGGAGTC-3'

antisense primer: (SEQ ID NO. 16)
5'-GAAGATGGTGATGGGATTTC-3'.

Probe: (SEQ ID NO. 17)
VIC-5'CAAGCTTCCCGTTCTCAGCC-3'-TAMRA

DNA and mRNA were extracted from cryopreserved lymphocyte samples and processed as previously described. (Mora, 2001 #6436; Cheung, 2001 #5733) Every PCR run was in duplicates and included a 5-point standard to generate a standard curve for scFv and for its corresponding endogenous control, plus a no template control. scFv standard was prepared from purified plasmid DNA, while β-actin and GAPDH standards were purchased from ABI. For DNA samples, scFv copy number was normalized by the β-actin level. For cDNA samples, scFv transcript was normalized to that of GAPDH. The variation in the quantitation from experiment to experiment was within 15%. Western blotting was carried out on lysate of scFv-modified T-cells using murine monoclonal anti-zeta antibody (BD Biosciences, Pharmingen, San Diego, Calif.; clone 8D3, 1 ug/ml final dilution) and HRP conjugated goat-anti-mouse affinity purified antibody (Jackson Immunoresearch, 1:1000 final dilution) as previously described. (Maher, 2002 #6433)

Cytotoxicity Assay Neuroblastoma targets NMB-7 and LAN-1, or rhabdomyosarcoma target HTB-82 were labeled with $Na_2{}^{51}CrO_4$ (Amersham Pharmacia) at 100 uCi/10^6 cells at 37° C. for 1 hour. After the cells were washed, loosely bound ^{51}Cr was removed by washing. 5000 target cells/well were admixed with lymphocytes to a final volume of 200 μl/well. Following a 3 minute centrifugation at 200×g, the plates were incubated at 37° C. for 4 hours. Supernatant was harvested using harvesting frames (Skatron, Lier, Norway). The released ^{51}Cr in the supernatant was counted in a universal gamma-counter (Packard Bioscience, Meriden, Conn.). Percentage of specific release was calculated using the formula 100%×(experimental cpm−background cpm)/(10% SDS releasable cpm−background cpm), where cpm are counts per minute of ^{51}Cr released. Total release was assessed by lysis with 10% SDS (Sigma-Aldrich), and background release was measured in the absence of cells. The background was usually <30% of total for these cell lines.

ELISPOT Assays 96-well PVDF plates (MAHA 54510, Millipore, Bedford, Mass.) were coated with 100 ml of anti-

IFNγ monoclonal antibody (10 μg/ml, Endogen, Woburn, Mass.) overnight at 4° C. The plates were washed with RPMI 1640 and then blocked for 1.5 hour at 37° C. with IMDM supplemented with glutamine (Gibco-BRL), penicillin, and streptomycin (Gibco-BRL), and 10% pooled human AB serum (Gemini). To transduced human lymphocytes (10^5/ml in medium containing 10% human serum, and 100 μl/well) tumor targets were added at various effector:target ratios and cultured for 26 hr at 37° C. in 5% CO_2. Plates were washed free of cells and reacted with biotinylated anti-IFNγ (2.0 μg/ml) for 3 hr at room temperature, before washing and reacting with a 1:1000 dilution of streptavidin-HRP conjugate (Zymed Laboratories, South San Francisco, Calif.) diluted in PBS containing 0.5% BSA for an additional 1-2 hr at room temperature. The colorimetric substrate was 3-amino-9-ethyl-carbazole (Sigma-Aldrich) at 0.33 mg/ml in 50 mM sodium acetate buffer (pH 5) containing 0.015% hydrogen peroxide. After incubation at room temperature for 8 min, the color reaction was stopped by rinsing the plates under running tap water and Elispots counted under a microscope.

Adoptive cell therapy of human xenograft in immune deficient mice CB-17 SCID-Beige mice were purchased from Taconic (Germantown, N.Y.). Two types of tumor models were used, a Winn assay (Wang, 1980 #6517) and an established tumor model. In the Winn assay, tumor cells (10^6 cells) were mixed with T-cells at various tumor-lymphocyte ratios and planted in 100 ul of Matrigel (BD BioSciences, Bedford, Mass.) subcutaneously. Following implantation, tumor sizes (product of orthogonal diameters) were measured. In established tumor model, tumor cells (2×10^6 cells) alone were planted subcutaneously. Here, cell therapy was started in groups of 5 mice per cage when tumor diameter reached 0.8 cm, usually by 1-2 weeks of tumor implantation. Mice received 5 weekly intravenous CIR-gene modified lymphocyte injections by retroorbital route, 2×10^6 per injection together with 500 U of IL-2 ip. 50 ug of anti-idiotypic or control antibody was administered ip 3 days after each lymphocyte injection. Tumor sizes were measured twice a week. Experiments were carried out under an IACUC approved protocol and institutional guidelines for the proper, and humane use of animals in research were followed.

Statistical Analysis Data were calculated as Mean+/−SEM. Differences between treatment groups were tested for significance (<0.05) by student t-test.

Results

Construction of sc8H9-CD28-hTCR-ζ-pMSCVneo Using synthetic oligodeoxynucleotide primers 355S, 355A for the hCD8a leader-scFv-CD28, 365S, 365A for scFv8H9, and 379S, 379A for hTCR-ζ-chain, the gene hCD8-leader-8H9scFv-hCD28TM-hCD28cyto-TCRζ was constructed, sequence-verified and transfected into the amphotropic packaging line GP+envAM12, and selected in G418. Enrichment and cloning of producer lines by affinity chromatography and cell sorting. The retroviral producer lines were affinity-enriched using MACS goat anti-rat IgG microbeads on the MiniMACS system. Following each enrichment, viral supernatant from the producer line was used to infect the indicator cell line K562. Surface 8H9-scFv expression on both the producer lines and the transfected K562 (4 days after infection) were measured by immunofluorescence using anti-idiotypic antibody 2E9. With each successive affinity enrichment (FIGS. **7***a* and **7***c*) of producer line and subsequent successive subcloning (FIGS. **7***b* and **7***d*), the surface expression (mean fluorescence) of 8H9-scFv increased and became more homogeneous for the producer clones (FIGS. **7***a* and **7***b*) as well as indicator line K562 (FIGS. **7***c* and **7***d*). Table 1 summarized the length of time (in weeks) required to enrich for scFv-positive producer cell line.

Retroviral transduction of primary human peripheral blood mononuclear cells Following in vitro activation with anti-CD3 and anti-CD28, primary human PBMC were infected with the virus from producer line supernatant by centrifugation at 1000×g for 60 minutes at room temperature. Using PBMC from normal volunteers, the in vitro requirement of IL2 and anti-idiotypic antibody for lymphocyte expansion was studied (FIG. **8**). On day 10 after gene transduction, 17-40% of cells became scFv-positive by FACS analysis. By day 15, 75-80% became positive and by day 24, 99% of the cells became positive. This clonal evolution to homogeneity was found in CD4+, CD8+ and the small CD56+ populations. IL-2 concentration of 50 to 100 U/ml appeared optimum, and anti-idiotypic MoAb 2E9 was absolutely necessary to maintain prolonged T-cell growth (FIG. **8**). These experiments were repeated twice with similar results. In the presence of 100 U/ml of IL2 and solid-phase anti-idiotypic antibodies, PBMC from 4 patients with stage 4 neuroblastoma off chemotherapy and 4 separate specimens from two normal volunteers, were expanded in vitro following CIR-gene transduction (FIG. **9**). Continual expansion (10^3 to 10^8 fold) was achieved after 150-200 days of culture, with a doubling time ranging from 5 to 10 days. 8H9scFv average gene copy number, transcript level, and surface expression were studied in these samples (FIG. **10**). The scFv-positive population enriched quickly during the first 20 days of culture in the absence of 2E9 (FIG. **10***a*). As expected, the gene copy number and transcript level also plateaued with similar kinetics (FIG. **10***b*). When the scFv-positive population became >95%, an average of 4.5 gene copies per cell (range 2-9) was detected, which remained relatively stable throughout the extensive length of in vitro culture. ScFv expression was typically >95% throughout 6 months of culture (FIG. **10***a*). By western blot analysis, the scFv-CD28-zeta chimeric protein was primarily a tetramer (MW-210 kD) under nonreducing conditions and a monomer of 54 kD in the presence of 2-mercaptoethanol. The proportion of CD8+ cells versus CD4+ cells increased steadily to >50% by day 40 of culture, and decreased slowly over 3-4 months. At concentrations of IL-2<50 U/ml, CD4+ cells outgrew the CD8+ population even faster (data not shown). T-cells expanded in the presence of anti-CD3, anti-CD28 and IL-2 (Koehne, 2002 #6442) were unable to kill HTB-82 cells in vitro (data not shown).

Transduced lymphocytes mediated non MHC-restricted antigen-specific cytotoxicity in vitro against neuroblastoma and rhabdomyosarcoma cell lines In vitro cytotoxicity against NMB-7 (FIG. **11***a*) and LAN-1 (FIG. **11***b*) neuroblastoma, or rhabdomyosarcoma HTB-82 (FIG. **11***c*) were efficient. Antigen-dependence was demonstrated by the total inhibition of cytotoxicties by MoAb 8H9 (FIG. **11**) and anti-idiotypic antibody 2E9 (data not shown). Daudi cell line (FIG. **11**D) was not killed because it was antigen-negative. This cytotoxicity was independent of target HLA expression or HLA types (data not shown). Unmodified lymphocytes from the same donor, cultured under the same conditions (100 U/ml of IL2), did not show antigen-specific killing (FIG. **11**). Control (5F11scFv) CIR modified lymphocytes also did not show antigen-specific killing of HTB82 (data not shown). In Elispot assays, IFN-7 secretion was detected when transduced lymphocytes were stimulated with antigen-positive tumors (NMB7 and HTB82) but not antigen-negative controls (Daudi, data not shown).

Adoptive cell therapy of rhabdomyosarcoma xenograft in SCID mice. Human rhabdomyosarcoma is strongly reactive with 8H9, but not with 5F11 (anti-G_{D2}) antibodies.

5F11scFv-CIR contained the same CD28-TCR construct used for 8H9scFv-CIR. 8H9scFv-CIR gene-modified lymphocytes suppressed HTB82 tumor growth, when mixed at 1:0.5 (tumor to T-cell), 1:1 or 1:10 ratios at the time of tumor implantation (FIG. **12**). While all the mice in control group (tumor alone) or irrelevant T-cell (5F11scFv-CIR gene-modified lymphocytes) group developed rapid tumor growth, in the presence of specific T-cells (8H9), tumor was completely suppressed. When anti-idiotype 2E9 was injected q 3 days×3 after tumor implantation, the anti-tumor effect was substantially reduced, in contrast to control antibody 1G8 or saline control. This inhibitory effect of 2E9 on the effector phase was consistent with in vitro findings (FIG. **11**). However, when 8H9scFv-CIR gene-modified lymphocytes was tested in an established tumor model, the growth sustaining function of specific anti-idiotypic antibody became more apparent. Here experiments were initiated when tumors grew to around 0.8 cm diameter. Control groups were injected with either (1) no cells plus 2E9 ip, (2) 5F11scFv-CIR modified lymphocytes intravenously plus anti-idiotype 1G8 (specific for 5F11 idiotype) ip or (3) 8H9scFv-CIR modified lymphocytes intravenously plus A1G4 (irrelevant anti-idiotypic antibody) ip. Suppression of tumor growth was most significant with lymphocytes transduced with the 8H9scFv-CIR gene (o) (FIG. **8**, $p<0.05$), and only if the specific anti-idiotype 2E9 was administered. 5F11scFv-CIR modified lymphocytes or 8H9scFv-CIR plus A1G4 did not show significant anti-tumor effect when compared to control. This in vivo effect of gene-modified lymphocytes was demonstrated in 3 separate experiment.

Discussion

We have demonstrated that primary human lymphocytes could be stably transduced with a scFv-CD28-ζ fusion gene carried by a retroviral vector to express surface scFv. Anti-idiotypic antibody directed at the scFv facilitated the cloning of the producer cell line and monitoring of gene expression. These CIR-gene modified lymphocytes could proliferate in the presence of anti-idiotypic antibody to undergo 10^6 expansion in both CD4+ and CD8+ populations over a period of 6 months. These cells responded in an antigen-specific manner in vitro by cytokine release and tumor cytotoxicity. By virtue of their near 100% CIR expression, they were more efficient than T-cells activated in the presence of anti-CD3/anti-CD28 and IL2. They effectively inhibited tumor growth in a xenograft tumor model in a Winn assay as well as in an established subcutaneous tumor model where T-cells were injected intravenously. Gene transduction was successful whether lymphocytes were derived from normal volunteers or patients. Our data suggest that although the CIR alone permitted survival of transduced lymphocytes during the first 3 weeks, anti-idiotypic antibody was necessary for proliferation beyond this initial period. Several observations on the scFv-modified T-cells were novel: the chimeric immune receptor homodimerized to a tetrameric form, T-cells expressing CIR demonstrated growth and survival advantage, anti-idiotypic antibody could inhibit effector phase during tumor killing in vitro and in Winn assay, but enhanced tumor suppression in the established tumor model.

The use of retroviral vectors to transduce chimeric immune receptors into primary human lymphocytes has been limited by the low gene transfer efficiency when viral supernatant infections were carried out. Transfer rates into primary human T cells using amphotropic virus ranged from 1 to 12%. (Bunnell, 1995 #4550) Several strategies were explored to increase the transduction rates to 20-50%. These include: (1) using gibbon ape leukemia virus (GaLV strain SEATO) pseudotyped virions, (Miller, 1991 #3388; Lam, 1996 #4553; Krause, 1998 #3956) (2) coculturing producer and target cells, (Bonini, 1997 #4716) where the clinical safety was of some concern, (3) using phosphate depletion followed by centrifugation and incubation at 32° C., (Bunnell, 1995 #4550) (4) adding fibronectin CH296 to enhance virus/lymphocyte interactions. (Pollok, 1998 #4506) More recently, Eshhar et al described a dicistronic construct consisting of scFv-CD28-γ and green fluorescent protein (GFP), where the latter was used to monitor gene transduction and to enrich producer line. (Eshhar, 2001 #5665) In the inventor's study, we used anti-idiotypic antibody to select for high surface scFv-expressing producer lines with improved efficiency of gene transduction. More importantly, lymphocytes transduced by CD-28-ζ chimeric fusion receptors could survive and proliferate in the presence of the anti-idiotypic MoAb maintaining their monoclonality with respect to scFv expression, in both the CD4+ and CD8+ populations. These receptors mediated antigen-specific cytokine release and cytotoxicity that was non-MHC restricted. Whether NK cells (CD56+ population) could acquire similar abilities will need further studies, since CD28 signaling in these cells was only rarely documented. (Galea-Lauri, 1999 #5609) Using this anti-idiotypic antibody strategy with minor modifications, we have successfully extended these findings to the G_{D2} antigen system (unpublished data). Recent studies have demonstrated the potential of CIR in retargeting EBV-specific cytotoxic T lymphocytes, (Rossig, 2002 #6479) a potential new source of effector cells that could persist and function long term after their transfer to cancer patients. We have also successfully transduced these scFv-CIR genes into EBV-specific cytotoxic T-cell populations (Koehne, 2000 #5893) to permit their in vitro clonal expansion of 10^6-fold in 5 months (unpublished data).

The advantage of using anti-idiotypic antibody for affinity purification and for clonal expansion of gene-modified lymphocytes are many fold. Being immunoglobulins, their structure, stability, biochemistry are generally known. This is in contrast to natural antigens where each individual system has its unique and often difficult-to-predict properties. As surrogate antigens, anti-idiotypic MoAb are ideal for standardization and quality control, especially for initial clinical investigations of carbohydrate antigens or when the nature of the antigen is not fully understood. To prepare polyclonal CTLs specific for a tumor target, lymphocytes have to be pulsed periodically in vitro with the tumor cells. (Koehne, 2000 #5893) The possibility of tumor contamination raises safety and quality control issues. More importantly, TCR ligation usually leads to activation-induced cell death. (Lenardo, 1999 #6439; Beecham, 2000 #6440) In CIR technology, scFv-CD28-ζ and scFv-CD28-γ constructs recruit costimulation to sustain T-cell survival. (Alvarez-Vallina, 1996 #4698; Beecham, 2000 #6440; Maher, 2002 #6433; Eshhar, 2001 #5665; Haynes, 2002 #6477) In our studies, anti-idiotypic antibodies stimulated T-cell proliferation and survival. Another advantage of anti-idiotypic MoAb is its ability to mark the clonal population of target-specific lymphocytes. Although tetramers can mark TCR and T-cell clones, identity of the peptide antigen is required and tetramer technology is not widely available. Furthermore, anti-idiotypic MoAb can mark T-cell clones in vivo when radiolabeled, an option not yet possible with tetramers. Finally, the potential of anti-idiotypic MoAb to activate transduced lymphocytes in vivo is appealing, especially when tumor cells are poorly immunogenic, or when they are scarcely distributed. The observations of the inhibitory effect of anti-idiotype in the Winn assay were consistent with their in vitro inhibitory effects during the effector phase. However, in the established tumor model, anti-idiotype was able to enhance tumor suppression. Given its ability to sustain

CIR-modified T-cell growth in vitro, a likely explanation was a similar supportive function in vivo in the established tumor model. One could speculate that anti-idiotype might also enhance the homing properties of these gene-modified T-cells. Clearly, a better understanding of in vivo homing properties and proliferative capacity of transduced cells in the presence or absence of anti-idiotype will be needed.

Previous studies suggest that the choice of the appropriate spacer (between scFv and signaling molecule), transmembrane domain and the signaling molecules were important. (Patel, 1999 #4695) That 8H9scFv-modified T-cells survive and proliferate in the presence of specific anti-idiotype and kill antigen-positive tumor cells argue strongly that the CD28 trans-membrane domain in this CIR design does not require a CD8 hinge, permitting effective interaction with soluble as well as cell-bound antigens. These results agreed with those recently reported by Maher et al. (Maher, 2002 #6433) It is of interest that in the absence of anti-CD3/CD28 antibody activation, gene-modified lymphocytes had consistent survival advantage during the first 3 weeks in culture, even without anti-idiotype. Since these fusion proteins can homodimerize, (Krause, 1998 #3956; Maher, 2002 #6433) signaling through spontaneous oligomerization may have provided initial survival advantage on gene-modified lymphocytes, although growth could not be sustained unless anti-idiotype is provided. Although the total increase in T cell number is comparable to anti-CD3/CD28 mediated in vitro expansion (Maus, 2002 #6438) the rate of increase is slower (2 to 3-fold), with significant cell loss during the first 3 weeks. It is possible that the transduction protocol can be improved to reduce direct toxicity from the viral supernatant. Signaling may also be improved by the addition of a hinge or the adoption of other trans-membrane domains. (Fitzer-Attas, 1998 #5955; Patel, 1999 #4695; Jensen, 1998 #4699) Moreover, using domains or molecules (wild type or genetically modified) further downstream in the T-cell activation pathway might potentially increase signaling, or even overcome the T-cell defects commonly found in cancer patients. (Eshhar, 1998 #5952)

The choice of tumor system and antigen target will likely determine the clinical success of CIR strategy. Primary lymphoid tumors such as B-cell lymphomas have distinct attributes. T-cells have an innate tropism to lymphoid tissues. These tumors also have unique tumor antigens with homogeneous expression that do not modulate from the cell surface (e.g. CD20). Furthermore, these B-cell tumors express costimulatory molecules. (Jensen, 1998 #4699) In contrast, most solid tumors lack these attributes. However, metastatic cancers in lymph nodes, blood and bone marrow are unique compartments where CIR technology may be applicable. Depending on the compartment, targeting of T-cells may require different chemokine receptors or adhesion molecules. For example, while L-selectin is required for homing to lymphoid organs, its role for trafficking to other metastatic organs such as marrow is less well defined. The precise evaluation of the quantity and persistence of these cells in vivo, as well as their distribution and function within tissues is likely to be critical. (Yee, 2001 #5674; Ma, 2002 #6437) In studies of T-cell therapy, this is of particular importance since many infused cells will undergo activation-induced death in vivo, (Lenardo, 1999 #6439; Beecham, 2000 #6440; Xiaoning, 1999 #5677) or immune elimination of gene-modified cells may occur, especially following repeated injections. (Riddell, 1996 #5963) The development of sensitive, accurate and reproducible methods to quantify gene-marked cells in peripheral blood and tissues are essential for defining the long-term fate of adoptively-transferred cells. While PCR and quantitative RT-PCR methods are ideal for studying tissues extracts, anti-idiotypic MoAb will provide useful a tool to enumerate individual scFv-positive cells in blood, marrow and tumor. In addition, noninvasive imaging methods using radiolabeled anti-idiotypic MoAb may also be possible. Similar to the marker gene HSV-tk that allows cells to be tracked and quantified by the substrate ^{131}I-FIAU or ^{124}I-FIAU, (Koehne, 2000 #5631) anti-idiotypic MoAb labeled with either ^{121}I or ^{124}I can also take advantage of instrumentation and software developed for SPECT and PET/microPET imaging, respectively. These tools can provide unprecedented precision and dynamic information on cell traffic in patient trials.

Retroviral vector MSCV carrying the gene for either 8HscFv-CD28, 8HscFv-CD28-ζ, or 5F11-scFv-CD28-ζ was transfected into packaging lines PG13 or GP+envAm12. The producer lines were then subcloned, affinity purified or FACsorted as detailed in Materials and Methods. The producer lines were analyzed for scFv expression by flow cytometry on day 4 after gene transduction.

Third Series of Experiments

ScFv-Modified Lymphocytes for Tumor Targeting

The plasticity of adult stem cells offers great promise in cell-based therapies. Hematopoietic stem cells give rise to all blood cells and have been used to treat serious blood disorders, malignant disease, and inherited diseases. These cells can differentiate into cardiac muscle cells, vascular cells, lung epithelia, neural cells, glial cells and other cell lineages. Developing tools to study both adult and embryonic stem trafficking in cellular therapies will provide a critical understanding of the real potentials and limitations of these approaches. While technical difficulties in gene modification of human stem cells have yet to be overcome, the human lymphocyte is a useful model to explore various in vivo imaging receptors, their targeting capacity, as well as the molecular biology and biochemistry of trace labeling methods.

Antibody-based targeting exploits the molecular specificity of the immune system. Utilizing single chain v-fragment (scFv) derived from monoclonal antibodies, chimeric immune receptors (CIR) can now be permanently transduced into primary human T-cells to redirect them to the specific antigen. In the last grant period we developed a technology based on anti-idiotypic antibodies to improve the rapid cloning of efficient producer lines for gene transduction. Using anti-idiotypic antibody as antigen surrogates, the propagation and expansion of these CIR-modified T-cells in vitro is highly reproducible. In this competitive renewal, we propose to compare the three imaging genes HSV1-tk, hNIS, and somatostatin receptor type 2 (SSTR2) to study T-cell trafficking. We will take advantage of the large experience in somatostatin receptors and ligands, plus the recent development of ^{68}Ga for PET dosimetry studies. We will determine the biologic parameters that determine labeling of these cells, the radiobiological consequences, the minimum number of cells that can be detected at tumor sites, as well as the validation of quantitative methods of measurement models. We plan to test the hypothesis that substantial improvements in T-cell targeting efficiency is possible if CD4+ T-cells can be pretargeted to the tumor site, and if professional killer cells are used. The availability of a high-resolution animal scanner, the MSKCC MicroPET, plus the animal micro-CT will facilitate these studies. We will also benefit from prior developments under related DOE grants, which include 1) practical methods for production of ^{68}Ga and ^{124}I; 2) the quantitative PET imaging of positron-emitting radionuclides with complex spectra, such as ^{68}Ga and ^{124}I; and 3) a method for highly selective labeling of genetically modified tumor-specific immune cells, using the positron labeled tracer ^{124}I-fluoroiodo-arabinosyl-uridine (FIAU).

Objectives

Although cell-therapy using stem cells and lymphocytes have great clinical potentials, their trafficking patterns and integration into tissues especially in real-time are not well understood. Noninvasive methods to help fill this knowledge gap remains a critical priority. Human T-lymphocytes are potent vehicles in tumor targeting. Retroviral vectors can permanently gene-modify their cell-surface receptors to target to specific tissues. As the sophisticated homing biology of T-lymphocytes becomes elucidated, clinical application of adoptive cell therapy has gained wider attention. We used scFv gene-modified T-lymphocyte as a cell-therapy model to study the pharmacokinetics of their survival and proliferation ex-vivo and in vivo after reinfusion. In the last grant period, we succeeded in using anti-idiotypic strategy to optimize gene transfer, survival and proliferation of T-cells ex vivo. We have shown that these cells can target to tumor sites to achieve tumor control in xenograft models. We propose to use somatostatin receptor type 2 (SSTR2) to study cellular biodistribution, and compare with HSV1-tk and sodium iodide transporter (hNIS). We will take advantage of recent advances in quantitative PET using ^{68}Ga and ^{124}I. We propose to test the hypothesis that successful pretargeting of T-cell subpopulation can recruit other lymphoid populations to improve homing to the target antigen and that using preprogrammed professional killer cells can further improve targeting efficiency.

Specific Aim 1: Comparison of marker genes for lymphoid cells in ex vivo and in vivo labeling

1.1 HSV1-tk

1.2 Somatostatin receptor subtype 2 (SSTR2)

1.3 Sodium iodide symporter

Specific Aim 2: Pretargeting of CD4+ T-cells to improve adoptive cell therapy

Specific Aim 3: Improving tumor homing and tumor cytotoxicity by using professional T-lymphocytes (CTL) and NK92 for CIR gene-modification

3.1 Cloned killer cell line

3.2 Professional cytotoxic T-lymphocytes (CTL)

Importance of the Research

The study of stem cell biology in vivo can potentially broaden our understanding of human cardiovascular, lung, blood, or neural development. The homing, proliferation and differentiation of stem cells in vivo are not fully understood and are likely to be influenced by the microenvironment. Studies of stem cell homing to sites of tissue injury or specific tissue or organ sites, and the mechanisms underlying the homing process will provide important information if stem cell therapy is to be successfully exploited for human diseases. Stem cell homing research can benefit from tools optimized for studying T-cell targeting to human tumors. We chose scFv-chimeric immune receptor directed at solid tumors to explore T-cell trafficking behavior, and propose noninvasive methods to track them in vivo.

Antigen-specific T-cells have been successfully used in adoptive therapies in patients for viral infections and cancer. These pioneering works have refined the practical issues of T-cell isolation, cloning, expansion and reinfusion. Adoptively transferred donor-derived Epstein-Bar virus (EBV) specific CTL can effectively eliminate B-cell proliferative disorders in the post-transplant period, a dramatic proof of principle for both efficacy and safety. After a 2-3 log expansion within the first month of infusion, these CTLs can be shown to survive for months, a property probably important for their in vivo efficacy. Successes in this EBV-lymphoma model is due to: (1) high CTL clonal frequency, characteristic of pathogen-based memory, (2) exquisite specificity to a viral antigen, (3) high levels of MHC and costimulator expression in lymphomas, and (4) innate ability of T-cells to home to lymphoid organs. Using retroviral vector gene transfers, it is now possible to modify durably the genetic makeup of T-lymphocytes. Targeting them to tumors is an enticing strategy since they can proliferate and expand clonally, potentially amplifying the anti-tumor response, as well the tumor to nontumor ratio of the delivered entity (either cells, cell-associated protein, secreted protein or viruses).

Using anti-idiotypic reagents, scFv chimeric immune receptors (CIR) consisting of scFv-CD28-ζ-chain have been transduced into primary human T-cells to produce readily expandable, long-lived and efficient clonal killer cell populations. Such CIRs genes joining tumor-selective ScFv to T-cell signal transduction molecules bypass MHC requirement while coupling antigen-specific tumor recognition with T-cell activation/survival. In this proposal we hypothesize that tumor targeting can be substantially improved if (1) CD4+ T cells can be successfully targeted first to recruit inflammatory populations including CD8+ T-lymphocytes and natural killer cells, and (2) the anti-tumor effect can be increased by employing preprogrammed professional killer T-cells. We propose to study the trafficking of whole or separated T-cell subpopulations in vivo after gene marking with human somatostatin receptor type 2 (SSTR2), human sodium iodide transporter (hNIS) or HSV1-tk. These lymphocytes can be imaged with [$^{66/67/68}$Ga]-DOTA-DPhe^{1}-Tyr^{3}-octreotide (DOTATOC), free ^{131}I and ^{131}I-labeled 2'-fluoro-2'-deoxy-1-b-D-arabinofuransyl-5-iodo-uracil (^{131}I-FIAU), respectively. Lymphocyte biodistribution and clonal expansion in vivo will be measured by positron emission tomography (PET) using [$^{66/68}$Ga]-DOTATOC, ^{124}I and ^{124}I-FIAU for the respective imaging genes. Using professional cytotoxic T-cells and cloned killer line NK92 instead of naïve T-cells for CIR gene transduction, we envision a substantial improvement in the efficiency of gene-modified T-cells by virtue of their preprogramming for tumor cytotoxicity, since they have been selected for their repertoire of lytic enzymes, death inducing peptides and adhesion molecules.

Background and Significance

Despite dose-intensive use of chemotherapy and radiotherapy, metastatic solid tumors have a dismal prognosis with cure rates of <20%.[1-3] Our inability to deliver specific therapy to minimal residual disease (MRD) compromises patient's chance of long-term cure.

Single chain Fv. The ability to condense the binding site by genetic fusions of variable region immunoglobulin genes to form scFv has greatly expanded the potential and development of antibody-based targeted therapies.[4-7] Using phage display libraries, scFv can now be cloned from cDNA libraries derived from rodents, immunized volunteers, or patients.[8-11] Construction of the scFv is the critical first step in the synthesis of various fusion proteins, including scFv-cytokine,[12] scFv-streptavidin,[13] scFv-enzyme,[14] scFv-toxins,[15] bispecific scFv (diabodies),[16] bispecific chelating scFv,[17] scFv-Ig,[12] tetravalent scFv,[16,18] and scFv-retargeted T-cells.[19]

Targeting lymphocytes to tumors. Using retroviral vector gene transfers, it is now possible to modify the genetic makeup of a cell permanently. Targeting lymphocytes to tumors is an attractive strategy. Lymphocytes execute complex tasks that antibodies are unable to perform, by communicating with and recruiting other inflammatory/immune cells or initiating tumor apoptosis. More importantly, they can proliferate and expand clonally. This latter property can potentially amplify the anti-tumor response, the tumor to nontumor ratio of the delivered entity (either cells, cell-associated protein, secreted protein or viruses), for both cancer imaging as well as therapy. Antigen-specific T-cells have been successfully used in adoptive therapies in patients for viral infections and cancer.[20-24] These pioneering work have refined the practical issues of T-cell isolation, cloning, expansion and reinfusion. Adoptively transferred donor-derived Epstein-Bar virus (EBV) specific CTL can effectively eliminate B-cell proliferative disorders in the post-transplant period, a dramatic proof of principle for both efficacy and relative safety.[22,23,25] After a 2-3 log expansion within the first month of infusion, these CTLs can be shown to survive for up to 18 months.[22,26] This success in the EBV-lymphoma model was due to: (1) high CTL clonal frequency, characteristic of pathogen-based memory, (2) exquisite specificity to a viral antigen, (3) high levels of MHC and costimulator expression in lymphomas, and (4) innate ability of T-cells to home to lymphoid organs.

Tools for tracking T-lymphocyte homing and their clonal expansion are limited. Previous models of lymphocyte homing have utilized lymphokine activated killer lymphocytes (LAK) or tumor infiltrating lymphocytes (TIL). In animal models, they generally showed tumor-specific localization. Although short-term labeling with chromium (^{51}Cr) is routine for isotope release cytotoxicity assays, it failed when applied to WBC trafficking studies. Attempts to incorporate radiolabeled metabolites and metabolite analogs (including 2-fluororo-deoxyglucose (FDG), amino acids, and nucleotides,[27,28] to radioiodinate cell membrane lipids/proteins, to induce phagocytosis of ^{99m}Tc- or ^{111}In-labeled colloids,[29,30] to trap intracellular radioactive divalent cations (e.g. ^{55}Co and ^{57}Co),[31] or to tag with radiolabeled MoAb,[32-34] have met with limited success. Although ^{111}In-labeled WBCs are routinely used to detect sites of infection and inflammation,[35] and in research studies of white cell homing properties,[36] high specific activity can interfere with lymphocyte functions possibly accounting for the low % ID/gm in recent studies of tumor-sensitized lymphocytes,[37] or TIL[38] cells. More importantly, ^{111}In labeling is currently only possible ex vivo. No imaging agent is available to study T-cell kinetics and biodistribution over an extended period of time.

There were several limitations in these early studies of lymphocyte imaging. Only a small proportion of cells are actually labeled. In the case of ^{99m}Tc, its relatively short physical half-life (6 hr) limits imaging to less than 1 day post-injection. More seriously, these labeling methods are antigen non-specific; i.e. all cells exposed to the labeling agent are labeled regardless of their ability to bind to the tumor target. That may partly explain the suboptimal targeting of <0.02% injected cell dose per gram. The CTL precursor frequency against human tumors (e.g. melanoma) in peripheral blood mononuclear cells (PBMC) even after in vitro stimulation with IL-2/IL4 is generally low (0.1% to 0.0030).[39] In EBV-lymphoma, unstimulated peripheral blood CTL precursor frequency is less than 0.05% and is ineffective until in vitro EBV-restimulation to 0.8-4%.[40] The low CTL precursor frequency may account for many of the past failures in the studies of T-lymphocyte homing to tumors. Increasing the level of radiolabeling has limited success since more than 20 uCi ^{111}In/10^8 cells is known to damage white cell functions.[41]

T-bodies can redirect lymphocyte against human tumors. Adoptive cell therapy using ex vivo expanded tumor-selective T-cells can effect dramatic remissions of virally induced malignancies, a process critically dependent on clonal frequency, where rapid exponential expansion of specific CTL is required.[23,25] T-cells proliferate when activated (e.g. anti-CD3). However, apoptosis occurs unless a costimulatory signal (e.g. anti-CD28) is present.[42] However, human tumor targets often lack costimulatory molecules (e.g. CD80), or overstimulate inhibitory receptors (e.g. CTL4) such that the CD28 pathway is derailed. In addition, many tumors down-regulate major histocompatibility complex (MHC) molecules to escape engagement by the T-cell receptor (TCR). Through genetic engineering, chimeric immune receptors (CIR) linking tumor-selective scFv to T-cell signal transduction molecules (e.g. TCR-ζ chain and CD28) will activate lymphocytes following tumor recognition, triggering the production of cytokines and tumor lysis.[19,43-49] T-cell can also be genetically engineered to secrete cytotoxic cytokines,[50] toxins,[51] or to metabolize prodrugs.[52,53] Genetically engineered T cells for adoptive immunotherapy of cancer is gaining wider attention. To date, clinical experience with gene-modified T cells has been limited, and most studies are unpublished (Table 1).[49] Although preclinical models generally utilized CD8+ CTLs, most clinical trials are utilizing unseparated T cells, preselected with co-expressed drug marker, or administered in bulk without selection to avoid targeting of microbial drug resistance genes. Most of these infusions have been relatively well-tolerated.

TABLE 1

Clinical trials using T-cells gene modified with CIR[49]

Date	Phase	Disease	Antigen	Structure	Location	Investigator
1995	I	HIV	gp120	CD4-ζ	NIH	Walker
1996	I	Ovarian CA	FBP	sFv-γ	NCI	Hwu
1997-1998	II	HIV	gp120	CD4-ζ	Multi	Hege
1997	I	AdenoCA	TAG72	sFv-ζ	Stanford	Hege
1998	I	AdenoCA	CEA	sFv-ζ	Harvard	Junghans
2000	I	Lymphoma	CD19	sFv-ζ	City of Hope	Jensen
2001	I	Neuroblastoma	L1	sFv-ζ	City of Hope	Jensen
2002	I	Renalcell	CAG250	sFv-ζ	den Hoed CC	Bolhuis
2002	I	Melanoma	GD3	sFv-ζ	Harvard	Junghans

However, significant technologic gaps remain: (1) Gene transduction into primary human lymphocytes is inefficient, (2) Antigen specific T-cells cannot be easily enriched and expanded, (3) Optimal T-cell activation may require multiple signals, and (4) Demonstration of anti-tumor effect of these human T-cells in established tumor models has been difficult and so far unsuccessful in patients.[49] T-cell activation requires two simultaneous signals,[54] one signal provided through the TCR[55] and a second one is a costimulatory signal.[56] T-cells get their second signal from their CD28 molecules which recognize B7 on APCs and tumor cells, stimulating IL-2 production; otherwise apoptosis or anergy will occur in response to the TCR signal alone.[56] Primary T-cells transduced with the anti-GD2 scFv-ζ-chain or scFv-γ-chain CIRs were able to kill antigen-positive tumors selectively.[48] However, cell cultures could not be maintained for longer than 8 weeks even upon stimulation with antigen-positive tumor cells. In addition, T-cell function when measured by interferon-γ release decreased substantially during in vitro culture to 25% over 2 weeks. The inability of Fv-ζ receptors alone to activate resting T cells was demonstrated in a transgenic mouse model.[57] On the other hand, when an anti-tumor scFv-CD28 CIR was used,[58] a functional co-stimulatory signal was achieved. CIR with multidomains was recently described, where the intracellular domain of CD28 was ligated to the 5' end of TCR-ζ chain and introduced into Jurkat cells and primary human lymphocytes, with the expected "two signals" when scFv was triggered by tumor cells.[59,60] IL-2 production was 20 times more than CIR with ζ-chain only. Primary mouse CD8+ T lymphocytes expressing the scFv-CD28-ζ receptor secreted Tc1 cytokines, induced T-cell proliferation, and inhibited established tumor growth and metastasis in vivo, a process shown to be critically dependent on IFN-γ secretion.[61] Not all T-cell mediated immune responses are CD28-dependent, and in humans about 50% of CD8+ T cells are CD28-negative.[56,62] During CD28 costimulation, while CD4+ cells responded with sustained proliferation, CD8+ T-cells grew for a limited period only accompanied by an increase in apoptosis.[63] Other costimulatory molecules include members of the TNFR superfamily,[64,65] CD30[66] and OX40[67] for Th2, as well as CD27[68] and 4-1BB for Th1.[69] It is possible that while chimeric receptors containing CD28 will enhance CD4+ T-cell proliferation, those incorporating costimulatory molecules such as 4-1BB could enhance CD8+ T cell and other subpopulations to expand in vitro and possibly in vivo.

Progress Report

CIR gene modified professional killer cells: CTL and NK92 NK92, CD56+ cell line established from the peripheral blood of a 50-year-old male with rapidly-progressing non-Hodgkin's lymphoma (large granular lymphocytic) whose marrow was diffusely infiltrated with large granular lymphocytes (LGL),[87] kills a broad spectrum of leukemia-lymphoma and virally infected cell lines in vitro.[88] Its remarkable tumor cytotoxicity is probably due to its unique repertoire of activating NK receptors (NKp30, NKp46, 2B4, NKGD, E, CD28) with few inhibitory receptors (NKGA/B, low levels of KIR2DL4, ILT-2) commonly expressed on normal NK cells (Table 4).[89] In addition, NK92 expresses high levels of molecules involved in the perforin-granzyme cytolytic pathway as well as additional cytotoxic effector molecules including tumor necrosis factor (TNF)-superfamily members FasL, TRAIL, TWEAK, TNF-alpha, indicating the ability to kill via alternative mechanisms. NK92 cells can be expanded in vitro with IL-2 with a doubling time of 24 to 36 h. IL2 was also successfully transduced into NK92 which then proliferate independently of IL-2 for >5 months, with concurrent increase in both in vitro and in vivo cytotoxicity.[90] NK92 has been used for ex vivo purging of malignant BCR-ABL-positive CD34+ progenitor cells from stem cell autografts of CML patients.[91] In phase I clinical trials, children and adults with late stage malignancies have received repeated irradiated NK92 transfusions up to 9×10^9 cell dose without adverse reactions.[88] Patients had no evidence of anti-NK92 immune response. However, NK92's lytic activity against solid tumor targets is less predictable. 8H9-scFv-CD28-ζ has also been transduced into NK92 cells, and the high expressors sorted and cloned using anti-idiotype strategy as described for primary T-lymphocytes. These gene-modified NK92 cells can efficiently kill an expanded spectrum of tumor lines in vitro as well as suppressing human tumor xenografts in vivo.

Gene expression profile of CIR-modified T-cells and NK92

An analysis of inflammatory chemokines, cytokines and receptors, as well as interleukins and receptors gene expression among CIR-modified NK92 as well as CIR-modified T-cells (cultured for 70 days, 99.7% scFv-positive, 50% CD4+ and 50% CD8+, harvested during their exponential growth) was undertaken. The GEArray Q series cDNA expression arrays (SuperArray, Bethesda, Md.) were used for these assays. In brief, cDNA probes using 5 ug each of T cell RNA from CIR-gene modified blood lymphocytes, versus fresh and cultured control lymphocytes, were synthesized with biotin-16-UTP. Hybridization at 60° C. was carried out in a hybridization chamber with constant rotation overnight. After several washes, chemiluminescent detection was performed at room temperature. A 1:10,000 dilution of alkaline phosphatase-conjugated streptavidin was placed on the membrane after a 40 minute blocking step. After several washes, CDP-Star chemiluminescent substrate was added. The membrane was placed between two transparencies, and developed on X-ray film for 10 seconds. Data analysis of the image was based on SuperArray software (Eisen Lab, LBNL, UCB, CA) and GEArray Analyzer (SuperArray). Four gene chips were used: human inflammatory cytokine and receptor, human interleukin and receptor, human extracellular matrix and adhesion molecules, human cytokines and receptors. Experiments were repeated at least once. Gene expression values were normalized to that of GAPDH and values from multiple chips were averaged. CIR modified T-lymphocytes displayed remarkably similar profiles of interleukin plus receptor (Tables 5 and 6, minus=negative, W=weak, Y=strong expression) and chemokine plus receptor (Tables 7 and 8) as compared to cultured T-lymphocytes without CIR gene modification, consistent with the expectation that CIR gene transduction did not substantially change the phenotypes necessary for their immune functions. Furthermore, both gene-modified T and NK92 cells expressed common chemokines including RANTES, and a broad spectrum of interleukins (e.g. IL4, table 4) and interleukin receptors (e.g. IL15R, table 6) with potential importance in amplifying the anti-tumor response. In contrast to low/absent CCR7 (thereby allowing T-cell to recirculate instead of docking in lymph nodes), CCR5 highly expressed for both 8H9s-scFv-CD28-ζ modified T and NK92 cells (Table 8). Since IL7 receptor was not detected among either T-cells or NK92, while IL15 receptor was expressed by both, IL15 may be useful for enhancing the survival of CD8+ T-cells both in vitro and in vivo. Also of note was the low level or absence of IL-2 and IFN-γ when the cells were harvested while off anti-idiotypic antibody.

Transduction of HSV1-tk into primary human T-cells

HSV1-tk is a therapeutic gene, a marker gene, as well as a suicide gene. In order to examine the migration of genetically altered antigen-specific T lymphocytes to tumors after adoptive transfer in vivo, we exploited the capacity of transduced T cells expressing HSV-TK to selectively phosphorylate and trap in cells and incorporate into DNA radiolabeled thymidine analog 2'-fluoro-2' deoxy-1-D-arabinofuransyl-5-iodo-uracil (FIAU) (FIG. **7**). Gamma camera images and autoradiographs showed selective tumor localization of ^{131}I-FIAU-labeled HSV1-tk-transduced EBV-specific, HLA-matched allogeneic donor T cells in preclinical models, achieving 1-2% injected per gram of tumor, and tumor-to-normal tissue activity ratio >100:1. In contrast to conventional cell labeling methods which are non-selective; FIAU labeled only those lymphocytes with the HSV1-tk transgene, yielding a highly purified and highly target-specific lymphocyte population. In addition, HSV1-tk transduced primary human PBLs were sensitive to ganciclovir (0.01-0.1 uM) in vitro and in preclinical models (20 mg/kg bid×7 days). The ability of EBV-specific HSV1-tk transduced T-cells to home and kill subcutaneous EBV lymphoma xenografts was completely removed by ganciclovir treatment, thus allowing these gene-modified T-cells to be safely removed when necessary.

The cell-level dosimetry of lymphocytes labeled by incubation ex vivo with radioiodinated FIAU was critical since [^{131}I]-FIAU could interfere with T cell function. In this model, the FIAU uptake (i.e. labeling) of the lymphocytes is expressed as the accumulation ratio (AR=cpm per gram of cells/cpm per ml of medium). The absorbed dose to the lymphocyte nucleus to reference (r) time T_r, $D_n(T_r)$, is calculated as the sum of the medium (m)-to-nucleus (n) dose, D(n←m), and the nucleus-to-nucleus dose, D(n←n). D(n←m) was equated with the mean non-penetrating (np) radiation (i.e. β) dose, D_{np}, from radioiodine in the medium (assuming the presence of the widely dispersed unit density cells would not significantly perturb the electron flux and therefore the dose from radioiodine otherwise uniformly distributed in the medium) and D(n←n) was calculated assuming instantaneous cell uptake of [^{131}I]-FIAU and using the recently published MIRD cell S factors.[92]

$$\begin{aligned} D_n(T_r) &= D(n \leftarrow m) + D(n \leftarrow n) \approx D_{np} + D(n \leftarrow n) \\ &= \Delta_{np} \cdot T^*[A]_m / \rho + S(n \leftarrow n) \cdot [A]_m \cdot M_c \cdot \\ &\quad \sum_{i=1}^{r} AR_i \cdot \int_{Ti}^{Ti+1} e^{-\lambda pt} / \rho \end{aligned}$$

where

$\Delta_{np} = 0.405$ gm-rad/μCi-hr for ^{131}I,

T^* = time of incubation of the cells with ^{131}I-$FIAU \approx 2$ hr,

T_i = time from the start of the incubation in the [^{131}I]-$FIAU$-containing medium,

T_r = reference time from the start of the incubation in the [^{131}I]-$FIAU$-containing medium for which the dose is calculated

$\equiv 60$ hr (typical in vivo imaging time post-injection),

$[A]_m$ = activity concentration in medium (μCi/ml),

ρ = mass density = 1 gm/ml for both medium and cells,

$S(n \leftarrow n)$ = the nucleus-to-nucleus S factor (i.e. dose per unit cumulated activity

$= 1.43 \times 10^{-7}$ rad/μCi-hr for ^{131}I

AR_i = accumulation ratio at the time T_i from the start of the incubation in the [^{131}I]-$FIAU$-containing medium

M_c = mass of cell

$\equiv 1 \times 10^{-9}$ gm/cell as measured for T lymphocytes

λ_p = the physcial decay constant of radioiodine

$= 0.0036$ hr^{-1} for ^{131}I.

Based on the forgoing dosimetry model and as presented graphically in the FIG. **15**, the lymphocyte nucleus absorbed dose was calculated as a function of activity concentration in the medium and the accumulation ratio. To study the effect on T-cell function, [^{131}I]-labeled FIAU was incubated with HSV1-tk transduced T cells at 11 Ci/ml at 37° C. for 40 to 120 min in increasing activity concentrations of [^{131}I]-FIAU from 1.1 to 56 μCi/ml, washed and transferred to fresh ([^{131}I]-FIAU-free) medium for 72 hr, and then used in a 51Cr-release immune cytotoxicity assay (low effector:target cell ratio=5). There was no demonstrable diminution in immune function up to an absorbed dose (at the reference time of 60 hr) of 1,200 cGy. At greater doses (>1,900 cGy), there was a dose-dependent decrease in immune function.

Radioactive gallium labeled somatostatin analogue DOTA-DPhe^1-Tyr^3-octreotide (DOTATOC Table 9) for positron emission tomography imagine Radionuclide labeled somatostatin analogues selectively target somatostatin receptor (SSTR)-expressing tumors as a basis for diagnosis and treatment of these tumors. Recently, a DOTA-functionalized somatostatin analogue, DOTATOC has been developed. This compound has been shown to be superior to the other somatostatin analogues as indicated by its uniquely high tumor-to-nontumor tissue ratio. DOTATOC can be labeled with a variety of radiometals including gallium radioisotopes. Gallium-66 is a positron emitting radionuclide ($T_{1/2}$=9.5 hr; βy^+=56%) that can be produced in carrier free form by a low-beam energy cyclotron. SSTR targeting characteristics of ^{66}Ga-DOTATOC were studied in nude mice implanted with AR42J rat pancreas tumor, and compared with ^{67}Ga- and ^{68}Ga-labeled DOTATOC. The labeling procedure gave labeling yield ranged from 85-95% and radiochemical and chemical purity was >95%. In-vitro competitive binding curves and in vivo competitive displacement studies with an excess of unlabeled peptide indicates that there is specific binding of the radioligand to SSTR. Animal biodistribution data and serial microPET™ images demonstrated rapid tumor uptake and rapid clearance from the blood and all tissues except kidney. Maximum % ID/g values for tumor were 10.0+0.7, 13.2+2.1 and 9.8+1.5 for ^{66}Ga-, ^{67}Ga-, and ^{68}Ga-DOTATOC, respectively. Calculated tumor, kidney and bone marrow doses for ^{66}Ga-DOTATOC based on biodistribution data were 178, 109 and 1.2 cGy/MBq, respectively. ^{68}Ga labeled DOTATOC can be used for PET diagnosis and quantitative imaging-based dosimetry of SSTR positive tumors. ^{66}Ga-DOTATOC may also be used in higher doses for ablation of these tumors. However, kidney is the critical organ for toxicity (tumor/kidney ratio=1.64).[93]

Background and Statement of Work

Specific Aim 1: Comparison of marker genes for lymphoid cells in ex vivo and in vivo labeling: HSV1-tk, Somatostatin receptor subtype 2 (SSTR2) and hNIS

1.1 Herpes Simplex virus I thymidine kinase (HSV1-tk), In vivo methods for monitoring gene-modified cells have exploited the sensitivity of gamma-camera (SPECT) or PET imaging to detect intravenous radiolabeled compounds that localize to the products of transferred genes. These genes include enzymes that metabolize drugs (Herpes Simplex Virus-1 thymidine-kinase [HSV1-tk]), transport drugs across cell membranes (sodium-iodide symporter [NIS]), and ligand-binding surface receptors (type 2 somatostatin receptor [SSTR2][94-96] and the type 2 dopamine receptor).[97,98] HSV1-tk gene transfer can be detected by both gamma and PET imaging using radiolabeled prodrugs (e.g. ^{124}I-FIAU) that become entrapped in the cell after phosphorylation by the kinase [99-103] Given the limitations of in vitro radiochemical cell labeling, a marker gene that does not interfere with T-cell function is critical for biodistribution studies of adoptively transferred T-cells. Each of these three marker genes have their merits and disadvantages.

	HSV1-gk	SSTR2	NIS
Human origin	N	Y	Y
Substrate availability	+	+++	++++
Substrate safety record	±	safe	safe
PET capability	Y	Y	Y
Suicide function	Y	N	N
Cellular retention	Y	Y	N
Distribution	cytoplasmic	membrane	membrane

-continued

	HSV1-gk	SSTR2	NIS
Tissue specificity	Y	tumors; some normal tissues	thyroid/ stomach/ salivary gland

Key advantages of HSV1-tk include its suicide function and its specificity (i.e. not found in human solid tumors). However, there are several limitations: (1) To label HSV1-tk-gene modified lymphocytes in vivo may need high concentrations of FIAU is needed. The safety of iodine-labeled FIAU especially at high doses is unknown, while unlabeled FIAU itself has been linked to severe hepatic toxicity in clinical trials. (2) Iodine-labeled FIAU requires special and expensive radiochemistry, (3) Nuclear location of metabolized radiolabeled FIAU can damage cellular DNA, limiting the absolute amount of radioiodine per lymphocyte. (4) HSV1-tk is a foreign protein, potentially antigenic and allergenic. (5) HSV1-tk is an intracellular protein, the expression of which is hard to quantitate in live cells. (6) Suicide with ganciclovir requires cell division and can be compromised because of HSV1-tk gene deletions.[104]

1.2 Human type 2 somatostatin receptor (SSTR2) SSTR2[94-96] is a membrane receptor that can be imaged with radiolabeled peptide ligands including ^{99m}Tc-P829 [NeoTect, Amersham Health, Princeton, N.J., FDA approved],[105] ^{188}Rh-P829, ^{99m}Tc-P2045, and ^{111}In-octreotide [Mallinckrodt] which is FDA-approved for total body imaging. We chose SSTR2 because it has been used extensively in clinical imaging with readily available radiolabeled ligands. In addition, a number of optimization strategy has already been designed, including intravenous L-lysine to reduce renal uptake. There are 6 SSTRs: types 1, 2A and 2B, 3, 4, and 5, all belonging to the 7-transmembrane domain family of receptors associated with G-proteins. Human type 2 has high affinity for octreotide, types 1 and 4 have low affinity,[106,107] and types 3 and 5 have intermediate affinity.[108-110] Types 2A and 2B are alternate splice variants where type 2A has a longer intra-cytoplasmic carboxy terminus than type 2B. SSTR2 expression has been reported in human lymphoid and leukemia cell lines, human peripheral blood lymphocytes especially when activated with PHA.[111] SSTR2 is the dominant receptor subtype expressed by inflammatory cells including T-cells.[112] Somatostatin and its analogs specific for SSTR2 enhance adhesion of T-cells to fibronectn.[113] ^{111}In-pentetreotide (octreotide) was used for predicting impending cardiac allograft rejection before endomyocardial biopsy becomes positive.[114] The inhibitory effect of somatostatin on lymphocyte proliferation[115] is mediated by SSTR-5.[116] When a panel of octreotide ligands were screened for their binding affinity and specificity (Table 9), Gallium labeled-DOTATOC was chosen for our studies because of its high affinity and specificity towards SSTR2 preferentially over SSTR5 which can interfere with the proliferation of gene-modified T lymphocytes.

1.3 Na$^+$/I$^-$ Symporter (NIS) Both rat and human NIS, a membrane-bound glycoprotein which is responsible for the thyroid gland's ability to concentrate iodide up to 40-fold with respect to plasma, was recently cloned,[117,118] and its genomic structure analyzed.[119] hNIS has 643 amino acid and a proposed secondary structure containing 13 transmembrane helices. NIS was upregulated with trans-retinoic acid in breast cancer cell line MCF7.[120] Prostate cell lines transfected with hNIS linked to a PSA promoter became sensitive to radioiodine therapy.[121,122], Adenovirus-mediated[123] or retrovirus-mediated[124] transfer of rat NIS into human carcinoma lines and human glioma cell lines[125] enabled rapid perchlorate-sensitive radioiodine uptake, in some cases to >200 fold. Xenografted tumors injected intratumorally with this adenovirus became iodine-avid accumulating 11% ID/gm. Prostate cancer (LNCaP) transfected ex vivo with the hNIS retained 25-30% of the total radioiodine with a biologic half-life of 45 h (30-60 h) and produced tumor shrinkage.[122] The slow efflux of iodide from NIS transduced cells can be partly explained by their lack of the efflux pump pendrin,[126,127] found exclusively in the thyroid but not other normal tissues.

Advantages and limitations of SSTR2 and hNIS to track T-cells are several fold. (1) Their radioligands are commercially available and inexpensive. (2) The safety and toxicities of the ligands are well known. (3) The bound ligands, unlike nucleotides, do not persist in DNA. (4) If transduced into T-cells, both hNIS and SSTR2 are human-derived and less likely to be antigenic or allergenic. (5) Clinical pharmacokinetics of the radioligands are well characterized, (6) SSTR2 and hNIS are surface proteins easily monitored with fluorescent or radiolabeled peptides or monoclonal antibodies, allowing high expressors to be potentially enriched by affinity column or flow cytometry. (7) Since it is naturally expressed by some activated T-lymphocytes, SSTR2 appears compatible with normal T-cell biology.

Neither NK92 nor CIR-gene modified T-cells expressed SSTR2 or showed spontaneous uptake of ^{111}In-Octreotide; thus SSTR2 gene transduction is necessary for imaging purposes. Surface receptor SSTR2 versus enzyme HSV1-tk approach have recently been compared in vitro and in vivo. Although uptake was equally good in vitro, in vivo imaging with HSV1-tk appeared inferior to SSTR2.[96] We expect radiometal labeled peptides to be rapidly endocytosed following binding to SSTR2, and become trapped intracellularly, unlike radioiodine which is metabolized and released. One major disadvantage of SSTR2 is its presence in a large spectrum of neuroendocrine tumors; here T-cell trafficking and tumors may not be easily distinguishable. Nevertheless, most sarcomas[128] and high risk (in contrast to low risk) neuroblastoma[129] have low expression of SSTR2. hNIS has a clear advantage over SSTR2 since few tumors except thyroid and possibly breast cancers express this protein. Although NIS can be transfected into human cells to express functional protein, the cellular consequences of the ectopic ion channel or iodine accrual on the human lymphocytes are unknown. There is also the concern on the membrane trafficking of the symporter. Although the leader sequence in the pVector would enhance membrane localization of the transgene, the rate of symporter turnover could affect the amount of radioiodine uptake. The efflux of iodide and consequently the short cellular half life can also be a limitation, especially if repeated imaging studies are needed. Nevertheless, this is a surmountable issue since radioactive iodine can always be readministered. Ironically this efflux could be an advantage, since radioactive iodide is rapidly excreted and less likely to damage lymphocyte function. It is conceivable that if retention of the iodide is needed, NK92 line can first be transfected with thyroid peroxidase enzyme to ensure organification.[130] One unique advantage of HSV1-tk is its suicide function that kills transduced cells in the presence of ganciclovir. Nevertheless, hNIS-transduced lymphocytes can potentially be killed by high dose of ^{131}I or ^{124}I, as demonstrated in NIS-gene modified tumor cell lines[120,122-125] and the thyroid gland.

General Plan of Work:

Comparison of HSV1-tk, hNIS and SSTR2 in gene marking of cloned killer lymphocytes

Marker	Ligand or substrate	
Gene	Gamma	PET
HSV1-tk	^{131}I-FIAU	^{124}I-FIAU
hNIS	^{131}I	^{124}I
SSTR2	^{111}In- DOTATOC Or ^{67}Ga-DOTATOC	^{68}Ga-DOTATOC

NK92 is a cloned killer cell line with well established characteristics (see Progress Report). EGFP (green fluorescence protein) was previously transduced into these cell lines and cloned, now used as our indicator line. Gene transduction will be carried out in two separate steps. First we use pDisplay vector from Invitrogen (Carlsbad, Calif.) to transduce either the SSTR2 or hNIS into NK92 cells as previously described.[96] A light chain 5' Igκ leader sequence for membrane localization plus a hemagglutinin (HA) tag will be inserted upstream of the SSTR2 and hNIS genes.[131,132], A stop codon will also be introduced into the 3' end to prevent expression in addition to the carboxy-terminal tail of SSTR2 or hNIS.[132] Since the binding domain for somatostatin is in the carboxyl end of SSTR2 between domains III and VII, amino terminal tag is not expected to interfere with receptor internalization.[132] Full length SSTR2 cDNA (type A)[133] was obtained from Dr. S Dorosio, U. of Iowa. Full length hNIS cDNA (2335 bp) was kindly provided by Dr. S. Jhiang of Ohio State University, Columbus, Ohio. Using anti-HA antibody (pDisplay vector), high expressors will be selected by affinity chromatography or cell sorting, and cloned in vitro. HSV1-tk was previously successfully transduced into NK92 using a discistronic vector, and selected with NGF (low affinity receptor) (see Progress Report). We have shown that NK92 can undergo multiple gene transductions and cloned without loosing its in vitro growth and cytotoxicity properties.

Specific Methods:

Saturation binding studies with $^{66/67/68}$Ga-DOTATOC Fresh cell membrane suspension (50 ug) on ice in 10 mM HEPES (pH 7.6, 20 μg/mL bacitracin, 5 mM $MgCl_2$ pH 7.6) is mixed in triplicates with increasing concentrations of ^{67}Ga-DOTATOC (5 pM-5 nM) either with or without 1 μM octreotide. The mixtures are placed on an orbital shaker for 45 minutes at room temperature before being diluted with 1 mL of ice cold saline buffer (150 mM NaCl, 10 mM Tris pH 7.4). The suspension is then rapidly (with vacuum) filtered over glass fibre filters (Whatman GF/C, presoaked in 1% BSA) and the tubes washed twice with ice cold saline (2×4 mL). The glass fiber filters were then removed before being counted with an automatic NaI(Tl) counter. For each data point, triplicates were performed. Specific binding is defined at the total binding minus the non-specific binding (i.e. in the presence of 1 μM octreotide). The data is then analyzed by saturation curve analysis. An analogous method was previously used to determine the binding affinity of DOTATOC for individual SSTRs expressed by transfected CHO cells (Table 9).

Kinetics of [$^{66/67/68}$Ga]-DOTATOC uptake and cellular dosimetry of indicator killer line NK92 SSTR2 gene modified lymphoid cells will be incubated in the presence of [$^{66/67/68}$Ga]-DOTATOC. Following incubation, cells will be washed twice with ice-cold medium and radioactivity measured in a γ-counter, and normalized to cell number. The human neuroblastoma cell line SKNSH transfected with hSSTR2 (kindly provided by Dr. S. Dorosio of U. of Iowa, IA) is used as a positive control. The time-dependent activity concentration in the cells will be calculated. To study cellular damage on NK92 or T-lymphocytes, cells are labeled by incubation for 2 hr with increasing radioligand concentrations, washed and transferred to fresh nonradioactive medium for 72 hr, and an aliquot tested in vitro for cytotoxicity in ^{51}Cr-release (at low E:T ratio) and IFN-(production. The rest of the NK92 are grown in fresh medium for 3 days, and their cell viability and cell number assayed. We want to confirm our previous results that cellular viability and immune function are not affected at absorbed doses (at 60 hr) of <=1,200 cGy. In addition to checking for immune functions, we will also establish a dose response curve for the level of radioactivity uptake and inhibition of lymphocyte proliferative capacity in a standard MTT assay.

Internalization and shedding of [$^{66/67/68}$Ga]-DOTATOC following SSTR2 receptor binding Internalization studies will be carried out using a modification of previously published methods.[134] Following [$^{66/67/68}$Ga]-DOTATOC binding at 4° C. (on ice) and unbound ligands removed by washing, cells are incubated at 0° C. or 37° C. for various time periods. Free ligand in the supernatant and PBS wash are counted in a γ-counter. Remaining [$^{66/67/68}$Ga]-DOTATOC on the cell surface are acid stripped by incubation with a buffer containing 0.05 M glycine HCl and 0.05 M acetic acid (pH 2.8-3) and 150 mmol NaCl for 5 min at 0° C.[135] The fraction of internalized ligand is calculated from the remaining radioactivity divided by the initially bound radioactivity.

Total cpm=free+acid-stripped+internalized

Cell bound=acid-stripped+internalized

% internalized=100*internalized/total cpm

% cell bound=100*cell bound/total cpm

% free=100*free/total cpm

$^{66/67/68}$Ga Labeling of DOTATOC^{66}Ga is produced by the cyclotron on site at Memorial Sloan-Kettering Cancer Center. ^{67}Ga is commercially available. Five microliters of carrier-free ^{67}Ga (930 mCi/mL, 0.05 M HCl) is added to 40 HL of 0.3 mM NH_4OAc (pH 7) and 4 μL of 1 mM DOTATOC. The reaction mixture is placed in a water bath at 100° C. for 15 minutes before a 1 μL portion is removed and diluted to 2 mL with 4 mM DTPA (pH 4.0). Fifty microliters of this solution is then analyzed by HPLC using C18 column (4 μm, 3.9×150 mm) and an eluant of 1.2 mL/min 20 mM NH_4OAc (pH 4), 0-60% acetonitrile gradient over 15 minutes. Typically incorporation rates are in excess of 99.5%.

^{68}Ga is eluted from a SnO_2 based ^{68}Ga/^{68}Ge generator in 5 ml of 1 M HCl. The concentration of HCl is increased to 5 M and the solution extracted with 2×1.5 mL diisopropyl ether. The ether fractions are pooled and evaporated under a stream of nitrogen. The concentrated ^{68}Ga (3-4 mCi) is then dissolved in 50 μl, of 0.3 M NH_4OAc and added to 3 μL of 1 mM DOTATOC. The mixture is heated at 100° C. before a 1 μL portion is removed and diluted to 1 mL with 4 mM DTPA (pH 4.0). The diluted solution is spotted onto two 10×1 cm ITLC-SG strips and developed in either 4 mM DTPA (pH 4.0) or 1 M NH_4OAC (pH7, 50% MeOH). In the pH4 TLC system the ^{68}Ga-DOTATOC remains at the origin with any colloidal $^{68}Ga(OH)_3$ and ^{68}Ga-DTPA migrates with the solvent front. In the pH7 system, colloidal $^{68}Ga(OH)_3$ remains at the origin and ^{68}Ga-DOTATOC and ^{68}Ga-DTPA move with the solvent front. Typically incorporation rates are in excess of 99.5%.

Kinetics of radioiodide uptake in NIS transfected cells and cellular dosimetry of NK92 hNIS Gene modified NK92 and T-lymphocytes will be incubated in the presence of carrier-free Na^{125}I (Amersham Pharmacia Biotech) and 10 μM NaI (to give a specific activity of 20 mCi/mmol), with or without 30 μM $KClO_4$. Following incubation, cells are washed twice with ice-cold medium and radioactivity measured in a γ-counter, and normalized to cell number. The rat thyroid cell line FRTL-5 (from ATCC) is used as a positive control. [^{131}I]-labeled labeled FIAU is incubated with HSV1-tk-transduced-NK92. The time-dependent activity concentration in the cells will be expressed as the accumulation ratio (see Progress Report). Next, the NK92 cells or lymphocytes are labeled by incubation for 2 hr with increasing radioligand concentrations, washed and transferred to fresh nonradioactive medium for 72 hr, and an aliquot then used in a ^{51}Cr-release immune cytotoxicity assay (at low E:T ratio). Another aliquot will be allowed to propagate in fresh medium for 3 days, and their cell viability and cell number measured. We will confirm our previous results that cellular viability and immune function are not affected at absorbed dose (at 60 hr) of at least 1,200 cGy. Since iodide is not sequestered in the nucleus, we expect the maximum tolerated dose to be higher for hNIS, which should improve scintigraphic imaging in vivo. A dose response curve for cytotoxicity will be constructed.

Iodide efflux assay The dose-dependent release of activity from NK92 or lymphocytes will also be evaluated as a function of post-labeling time. At various time after the incubation of the effector cells in ^{131}I containing medium and transferring to [^{131}I]-free medium, the activity remaining in the cells and leaking into the medium are assayed. The content of ^{131}I in the supernatant is measured by γ-counter. After the last time point, the cells are extracted with 400 μl ethanol to count residual radioactivity. The rat cell line FRTL-5 is used as a positive control.

Western Blot analysis Postnuclear membrane fractions will be prepared and western blot analysis performed using a rabbit anti-SSTR2 antibody (BioTrend, Chemicals, Destin, Fla.), using a murine monoclonal anti-NIS antibody (kindly provided by Dr. J. Struck of Brahms, Berlin, Germany), or anti-HSV1-tk antibody (Dr. Tjuvajev, MSKCC, NY) and horseradish peroxidase-conjugated anti-mouse IgG (Jackson Research Laboratories), and signal visualized by chemiluminescence. Quantitative analysis is performed using the NIH IMAGE program (http://rsb.info.nih.gov/nih-image/).

FACS analysis Cells expressing the HA-tagged SSTR2 can be monitored with anti-HA antibody (12CA5, Boerhinger-Mannheim, Indianapolis, Ind., or HB-66, ATCC, Rockville, Md.) or rabbit anti-SSTR antibody (Santa Cruz Biotechnology, Santa Cruz, Calif.). Cells expressing SSTR2 are first reacted with specific antibody or IgG control, washed and then reacted with FITC-goat anti-rabbit (if primary antibody is rabbit) or FITC-goat anti-mouse (if primary antibody is mouse monoclonal) affinity purified antibody (Jackson). Propidium iodide (10 μg/ml) is used to mark damaged cells, and excluded from the analysis. SKNSH neuroblastoma cell line will be used as the positive control for SSTR2 expression. The fluorescence of 5000-10000 cells/tube is assayed using the FACSCalibur cytofluorometer (Becton Dickinson). Cells expressing HA tag can be monitored with anti-HA antibody. Alternatively, hNIS without HA can be monitored with the MoAb from Brahms, Germany.

Quantitative measurement of T-cells in tissue sections In order to determine quantitatively the number of lymphocytes trafficking to the tumor site, we plan to perform 2 kinds of experiments: (1) extracting single cells from tumors and (2) by radiotracer technique. Single cell suspensions are prepared from a known weight of tumor using collagenase enzyme mixtures. After ficoll-gradient to remove debris and dead cells, the number of gene-marked lymphocytes are quantitated by flow cytometry using EGFP (NK92 only), anti-idiotypic antibody and marker-gene specific antibodies: anti-HA (for SSTR2), anti-hNIS, and anti-NGFR(HSV1-tk) antibodies. To avoid collagenase/protease modification of surface proteins fresh frozen tissue sections will also be analyzed by direct fluorescence (EGFP, NK92), or indirect immunofluorescene using specific antibodies. The relationship between cell dose injected and the number of T-cells/gm of tumor will be determined. Quantitative autoradiography can also be performed although they need to be correlated with histology. For cells carrying HSV1-tk gene, they can be labeled with ^{131}I-FIAU, or SSTR2 gene with ^{111}In or ^{67}Ga-DOTATOC, and hNIS labeled with ^{125} for radiotracer experiments.

Imaging and quantitative measurement of tumor infiltrating T-cells SCID mice xenografted with human tumors are injected i.p. with 2 ml of 0.9% NaI solution to block thyroid uptake of radioactive iodide. Gamma camera imaging and SPECT are performed with a dual-headed ADAC Genesys gamma camera (ADAC, Milpitas, Calif.) equipped with a HEHR collimator. Sequential images are obtained at 1, 4, 18-24 h after cell injection. PET images can provide highly accurate quantitation of radiolabeled cell distribution within the body. The PET protocol consists of scanning at 1, 4, 18 hr post infusion. For ex vivo labeling ^{66}Ga-DOTAOTC (T–½=9.5 h) or ^{124}1 can be used. For in vivo labeling, shorter half life isotope such as ^{68}Ga (T–½=68 min) will also be tested. Images will be reconstructed and attenuation corrected. Transaxial and sagittal slices will be studied in order to ascertain the uniformity of the radiolabel distribution. With micro CT fusion, for each time point, the specific activity of isotope per volume plotted over time can be calculated. Time activity graphs will be decay corrected for isotope in order to obtain a biological clearance curve.

Cell labeling in vivo after homing to tumor sites To test the concept of imaging scFv-CIR modified lymphocytes, animals are treated with NaI i.p. to block the thyroid uptake. No-carrier-added ^{131}I,^{124}I (for hNIS),^{131}I-FIAU or ^{124}I-FIAU (for HSV1-tk) and ^{111}In-DOTATOC or $^{66/67/68}$Ga-DOTATOC will be injected iv at 24 h, 48 h, or 72 h after T-cell injection, depending on when the maximal homing occurs from biodistribution experiments. Tumors in mice will be imaged by gamma (planar or SPECT) or PET where appropriate. Biodistribution studies at various time points will be done by tissue counting. Tissues will also be analyzed (direct and indirect fluorescence plus QAR.

Retroviral dicistronic construct Although imaging gene and CIR can be separately introduced into established killer lines like NK92, for primary human T-cells, both marker and CIR genes have to be transduced simultaneously. We utilize the bicistronic vector that contains the CIR, internal ribosome entry-site sequence (IRES), and SSTR2 or hNIS or HSV1-tk. Both SSTR2 and hNIS genes (with their leader or tag sequences from the pDisplay vector from Invitrogen, Carlsbad, Calif.) are first PCR amplified with appropriate primers (to make SalI-SSTR2-NotI) to swap with HSV1-tk in pIRES. Zeta chain will be inserted into MCS of pIRES using the fragment Xho1-zeta-Mlu1. After digestion with Xho1 and Not1, the ζ-IRES-HSV1-tk is swapped with ζ-chain in the scFv-CD28-ζ construct using Xho1 and blunt end ligation.

Anti-idiotype enrichment of viral producer line by cell sorting Building on initial successes with anti-idiotype enrichment of producer line, we will FACS sort the producer line to clone out the brightest 0.1% (following surface staining of producer line with anti-idiotypic antibody). This sorting can be repeated until there is no added improvement in mean fluorescence. The producer line is then subcloned using NK92 as indicator cells, and screened for scFv, SSTR2 (using anti-HA antibody) or hNIS (using anti-HA or MoAb specific for hNIS) gene expression by flow cytometry. Subcloning is repeated until a stable clonal producer line is obtained. The most efficient producer clone is selected for cell banking. We plan to use NK92 instead of K562 as indicator line because NK92 is relatively easy to transfect and clone and has great clinical potential. Previously we used centrifugation to effect viral attachment and infection of human lymphocytes (see Progress Report). We plan to further improve the efficiency of retroviral infection by using fibronectin fragment CH-296 (Takara Shuzo, Otsu, Japan), to augment gene transfer by interaction between VLA-4 on T-lymphocytes and FN adhesion site CS-1,[136] in conjunction with centrifugation.[137,138] In those reports, gene transduction increased from 12% to 18% with centrifugation and to 24% when centrifugation plus fibronectin was used.[138] The kinetics of surface SSTR2 expression and cytoplasmic HSV1-tk expression will be monitored. Day 40 scFv-modified lymphocytes will be analyzed for CD4 CD8, CD56, scFv, SSTR2 (or HSV1-tk) expression. After further expansion in culture, they will be analyzed for their iodine uptake and efflux. Protein expression can be confirmed by western blot and mRNA by Tagman quantitative RT-PCR[139] based on the known genomic/cDNA structure of SSTR2 and the fusion sequence of scFv-CD28-ζ. Gene copy number based on quantitative PCR method will also be used as previously described.[140]

Statistical analysis. Data are expressed as the mean±SEM. Statistical significance of differences is determined by conducting a paired Student's t-test.

Results In picking the winner (HSV1-tk, SSTR2, hNIS), the following criteria will be used:

1. maximal specific activity without damaging cellular function
2. maximal half-life (retention within cell)
3. maximal % ID/gm of ex vivo labeled lymphoid cells at 24 and 72 hours in tumor xenograft versus normal organs (liver, spleen and lung); for NK92 which grows as sc xenograft in SCID mice. Also considered is maximal % ID/gm of intravenous radiolabeled DOTATOC, radioiodine or radioiodinated FIAU.

HSV1-tk (~1 kp) gene transduction using IRES vector and its expression in human T-cells are now routine.[141] Although both hNIS (~2 kp) and SSTR2 have been transduced by retroviral vector into mammalian cells, efficiency of the IRES construct can vary. It is conceivable that the efficiency of gene transfer and gene expression could also vary between cloned line NK92 and primary human T lymphocytes. We plan to quantitate the gene copy number by real time PCR, mRNA by RT-PCR and correlate them with protein expression by flow cytometry and western blots. In vivo biodistribution of gene-modified NK92 cells and lymphocytes will be verified using immunostaining of mouse tissues and tumors employing biotinylated anti-idiotypic reagents. Alternatively, quantity of human lymphocytes in mouse tissues can also be measured by sensitive real time PCR (of transduced genes) as well as RT-PCR for mRNA using mouse ∃-actin and mouse GAPDH, respectively, to calculate relative copy number. We also plan to validate in vivo cell-imaging studies using radiolabeled anti-idiotypic reagents. Although anti-idiotypic reagents offer another alternative to marker genes for imaging T-cells, these reagents are not widely available as octreotide (already licensed by the FDA for total body imaging) and could be difficult to implement clinically.

In adoptive cell therapies, gene-marking allows precise evaluation of the quantity and persistence of these cells in vivo, as well as their distribution and function within tissues.[142] In studies of T cell therapy, this is of particular importance since many infused cells will undergo activation-induced death in vivo. [143] or immune elimination of gene-modified cells may occur, especially following repeated injections.[144] The development of sensitive, accurate and reproducible methods to quantify gene-marked cells in peripheral blood and tissues are essential for defining the long-term fate of transferred cells. Such pharmacokinetic information is crucial if understanding and optimization are to be pursued. We want to take advantage of instrumentation and software developed for SPECT and PET/micro-PET imaging. These tools will give unprecedented precision and dynamic information in future patient trials.

Specific Aim 2 Pretargeting of CD4+ T-Cells to Improve Adoptive Cell Therapy

The fate of CIR gene-modified T-cells in vivo remains unknown in most cases. Influx of inflammatory cells following local increase in vascular permeability during complement activation and release of anaphylatoxins is well known. An active process of recruitment may be equally if not more important in cellular immunity. The importance of recruitment by CD4+ T cells, chemokines and cytokines, as well as the myriad of adhesion molecules involved in lymphocyte rolling, adhesion, diapedesis, and movement within the tumor microenvironment have been previously emphasized.[145] Distinct roles for Th1 and Th2 for tumor eradication in vivo have recently been proposed. [146] While Th1 cells induce a marked lymphocyte infiltration into the tumor mass and eradicate tumor mass via cellular immunity and memory CTL, Th2 cells induce inflammatory responses and tumor necrosis through IL-4 recruitment of eosinophils and neutrophils. Th1 cells express high levels of P-selectin, and exhibit strong LFA-1/ICAM-1 dependent cell-cell interactions and Th2 cells interact with extracellular matrix through the integrins. Th1 cells are probably the lymphocytes responding actively to tumor cells and producing cytokines, which in turn recruit other effector cells including CD8+ T cells, NKT or NK cells into the tumor tissue. In contrast, Th2 cells, unable to enter tumor tissue because of their defect of adhesion, may accumulate on the endothelium and induce tumor necrosis via TNF-0 and/or release of reactive oxygen intermediates from eosinophils and macrophages to damage tumor vessels.

T cells homing depends on chemokines and receptors, clearly illustrated in allograft and graft rejection models.[147] CCR4, CXCR3, CCR5, and CCR7 are some of the key chemokine receptors for T-cell trafficking. CCR4 is the major trafficking receptor for systemic memory T cells. A pivotal role for CCR5 in T-cell migration to tumor sites induced by interleukin 12 treatment was recently reported. [148] CXCR3 is present on activated lymphocytes including CTL and NK cells.[149] Th1 cytokines and CXC3 chemokines can direct infiltration of adoptively transferred CD8+ T cells into the tumor site. CCR7, the lymph node-homing receptor, is expressed on CD4+ or CD8+ mature T cells. This is important since metastatic solid tumors often spread to marrow, bone, lung and liver. CCR7 downregulation may permit these cells to home to nonlymphoid metastastic sites. T-cells also play an important role in recruitment by using chemokines. RANTES enhances Th1 and CD8+CTL responses,[150] while CTLs can in turn release IL-8, MIP, RANTES, and IP-10.[151]

General Plan of Work:

Enrichment of CD4+ T-cells. In order to prepare sufficient numbers of T-cells for in vivo biodistribution studies, cultured CIR-gene modified T-cells (>95% scFv positive) will be purified into CD4+ and CD8+ populations by affinity chromatography using MiniMac System (Miltenyi).

Homing studies on separated CD4+ and CD8+ populations. Following CIR transduction and affinity purification, CD4+ cells will be checked by flow cytometry for surface phenotype and cytoplasmic cytokines, plus gene expression by microarrays. In addition, their antigen specific immune function will be checked in ELISPOT assays (IFN-γ). CD8+ cells will be analyzed likewise and their cytotoxicity confirmed in ^{51}Cr release assay. The misdistribution of [CIR+ imaging]-gene modified CD4+ and CD8+ T-cells will be studied in mice with and without tumor xenografts. PET will be used for imaging and quantitative dosimetry. At specific time points, mice will undergo necropsy and tissues harvested for gamma counting. CD4+ T-cells with CIR but no imaging gene will also be tested in the pretargeting model. Indicator cells (both NK92 and T-lymphocytes) carrying the imaging gene, with or without CIR, will be tested for their homing response to pretargeted CD4+ T-cells either by (1) radiolabeling in vitro before administration iv, or (2) radiolabeling in vivo after they have had time to home to the tumor sites.

Quantitation by PET will be validated with tissue extraction and analysis by flow cytometry (quantitation of scFv+ cells). Here, single cell suspensions will be prepared from tumors and organs (blood, spleen, liver, and lymph nodes) by mechanical disruption and coarse filtering. Live cells will be marked by propidium iodide and their CD3, scFv, CD4 and CD8 expression quantified. Tumor cells will be marked with anti-gp58 (MoAb 8H9) or anti-GD2 (MoAb 3F8) antibodies. Number of T cells will be expressed as percent of total cells and per gram tumor or tissue weight for comparisons. In addition, total DNA and RNA will also be tested for scFv gene copy number and scFv transcript number using PCR and RTPCR, and normalized to mouse ∃-actin and mouse GAPDH, respectively. Again these will provide independent validation for the quantitation techniques described above.

Specific Methods:

Phenotypic characterization In addition to gene array analysis (chemokine and receptors, interleukin and receptors) on the CD4+ and CD8+ cells, their surface and cytoplasmic phenotype will also be studied by FACS analysis at select time points during in vitro culture. These markers include CD4, CD8, CD25, CD45RO, CD69, VLA-4, LFA-1a, LFA-1-b, L-selectin, CCR4, CCR5, CXCR3, CRTH2, CCR7, cytoplasmic granzyme B, IL-2, IL-4, and IFN-(. Specific antibodies are obtained from the NIH AIDS Resource Program as well from commercial sources: anti-CCR3 (R&D systems, Minneapolis, Minn.), anti-CXCR3 (R&D), anti-CCR5 (Pharmingen, San Diego, Calif.), anti-CCR4 (Dr. Chantry, Icos Corporation, Bothell, Wash.) and anti-CCR7 (Pharmingen). Four color fluorescence will be performed: APC-anti-CD3, PerCP-anti-CD8, FITC-2E9 (anti-idiotype) and PE-antibody (specific for adhesion molecules, cytokines, and chemokine receptors). Appropriate controls will be included for channel compensation.

Intracellular cytokine expression For the detection of cytoplasmic cytokines, cells are first cultured in the presence of brefeldin A (Sigma), stained with PerCP-anti-CD4 MoAb, fixed with 4% paraformaldehyde, and treated with permeabilizing solution (50 mM NaCl, 5 mM EDTA, 0.02% NaN3, 0.5% Triton X-100, pH 7.5) before staining with PE-conjugated anti-IL4, and FITC conjugated anti-IFN-g for 45 min on ice. The percentage of cells expressing cytoplasmic IL-4 (Th2) or IFN-((Th1) is determined by flow cytometry.

Results We test the hypothesis that pretargeting of CD4+ T-cells can increase the homing efficiency of subsequent injections of NK cells and lymphocytes. Although NK92 is used as an indicator cell in our experiments, their broad antitumor activity and preliminary clinical applications are encouraging evidence of its clinical utility. Since the current limitation of adoptive cell therapy using killer cell lines like NK92 remains suboptimal in efficiency in tumor targeting, the ability of CD4+ T-cells to facilitate this tumor-homing property can potentially improve their anti-tumor efficacy, which we will test in xenografted SCID mice. Our studies will also attempt to characterize the ability of CD4+ T cells (armed with CIR) to recruit untargeted NK cells and untargeted T-lymphocytes (i.e. without CIR), and if this recruitment translates into significant anti-tumor effect. It is also possible that other human white cell populations as well as stem cells can be studied in this homing model. Although the SCID mice provide a model to test human T-cell homing, it has inherent limitations. For example, tumor stroma is mostly mouse-derived, not made up of human stromal cells, and thus are missing certain chemokines and cytokines that can positively or negatively modulate the T-cell homing properties. In addition, SCID xenografts are generally made up of mouse-derived vasculature, and as such will not interact with human lymphocytes or inflammatory cells in a physiological manner. Nevertheless, these tests will allow us to validate the imaging gene technique especially when applied in quantitative PET imaging of gene-modified T-cells. A noninvasive technique to quantitate lymphocyte trafficking will undoubtedly require much further refinement, and likely necessitates using human patients. Positive results from these studies will provide the rationale for further developments in their clinical translation.

Interpretations and implications The biology of chemokine receptors and adhesion molecules in directing T cell traffic is a rapidly advancing field. As the science of cytotherapy becomes more sophisticated, purer subpopulations of lymphocytes with defined functions will become available for in vivo studies. Understanding the cellular cascade in orchestrating tumor targeting will provide crucial information for diagnostic and therapeutic manipulations. Reliable methods to trace label these cells without damaging their cellular function are still technologic gaps in cytotherapy.

Specific Aim 3 Improving Tumor Homing and Tumor Cytotoxicity by Using Professional T-Lymphocytes (CTL) and NK92 for CIR Gene-Modification

General Plan of Work:

In both specific aims 1 and 2, we propose to use NK92 as our indicator line. NK91 is a cloned professional NK killer cell line. They have potential clinical utility in adoptive cell therapy in early human trials. Antigen specific CTLs, when highly enriched, are also efficient killing machines ideal for adoptive cell therapy. More importantly, these enrichment steps can also remove substantial numbers of alloreactive T cells, such that allogeneic CTLs may be safe to use. This is particularly relevant when one considers the paucity of healthy T cells in patients after intensive chemotherapy available for gene-modification. EBV-specific T cells can be selected early after in vitro sensitization, while alloreactive T cells are substantially depleted by this approach,[85] enriching the auto/allo ratio by 39-fold. Indeed these EBV-specific T cells can be continually boosted periodically with EBV-infected cells in vitro, and maintain their ability to home to and kill specifically EBV-lymphomas in vivo.[141] The specificity of these CTLs is exquisite, since allogeneic EBV-lymphomas are not killed.

Viral antigen-specific T cells have been successfully used in adoptive therapies in patients.[20-23] Adoptively transferred donor-derived EBV-specific T cells can effectively eliminate B-cell proliferative disorders in the post-transplant period: a dramatic proof of principle for adoptive T-cell approach in cancer therapy, emphasizing their efficacy and relative safety.[22,23,25] When genetically tagged with the neomycin resistance gene using a retroviral vector,[26] these CTLs can be shown to last for up to 18 months.[22] The persistence of these EBV-specific CTLs probably reflects a continual antigenic challenge from dormant EBV virus residing in the body after primary infection. Recently, Rossig et al have shown that these CTLs can be gene modified with scFv-CIR.[152] We have also demonstrated that complex scFv-CD28-. chimeric gene can be transduced into these CTLs whereupon continual clonal expansion>10^{5} fold for many months (Progress Report).

We propose to arm EBV-specific professional CTLs with scFv-CIR. As CTLs they are effective and safe, both in vitro and in vivo. They can be gene-modified using retrovirus. They mount effective amnanestic CTL response. And most importantly, using rapid in vitro selection,[85] alloreactivity can be eliminated. This approach will enable allogeneic CTLs to be used for scFv-based T cell therapy. EBV-specific CTLs from designated normal donors will greatly increase the efficacy and success of gene-modified T cells. More importantly, there is no chance of contamination by tumor cells if allogeneic T cells are used.

Specific Methods:

Production and culture of EBV-lymphoblastic cell lines PBMCs at a concentration of 1×10^{6}/mL will be incubated for 24 hours after isolation by Ficoll-Hypaque density centrifugation with the EBV containing supernatant of the marmoset cell line 95-8 in the presence of 0.5 ug phytohemagglutinin (PHA)-16 (Murex-Diagnostik, Norcross, Ga.) in RPMI 1640 (GIBCO, Life Technologies, Grand Island, N.Y.), 10% heat-inactivated fetal calf serum (FCS), 10 U/mL penicillin, 10 ug/mL streptomycin, and 1% L-glutamine. After 24 hours, cells are washed and recultured in EBV-containing medium without PHA in 24-well plates at a concentration of 1×10^{6}/mL. Cells are then fed fresh RPMI 1640 with 10% FCS, L-glutamine, penicillin, and streptomycin twice a week and expanded according to the growth and cell number. The cells are finally characterized by fluorescence-activated cell sorter (FACS) analysis using CD3, CD 19, and CD20 monoclonal antibodies (Becton Dickinson). Aliquots of the immortalized B-lymphoblastoid cell lines (BLCLs) are frozen and the remaining cells maintained in culture. Homozygous BLCLs for the HLA-A and HLA-B alleles, generously provided by Dr. B. Dupont of MSKCC are maintained in the same medium. PHA blasts are generated by culturing 1×10^{6}/mL PBMC with 0.5 ug/mL PHA-16 for 3 days. The cells were washed and further cultured for 4 days in the presence of 5 IU/mL interleukin (IL-2) (Collaborative Biomedical Products, Bedford, Mass.).

Generation and culture of EBV-specific CTLs PBMCs are isolated by Ficoll-Hypaque density centrifugation of anticoagulated whole blood. T lymphocytes are positively selected by staining with an anti-CD3 phycoerythrin monoclonal antibody (Becton Dickinson) on a MoFlo cell sorter (Cytomation, Fort Collins, Colo.), achieving a purity of more than 98%. EBV-specific CTLs are generated by stimulating 1×10^{6}/mL CD3+ cells with 2.5×10^{4}/mL autologous BLCLs, which are irradiated with 60 Gy in Iscove's modified Dulbecco's medium supplemented with 10% heat-inactivated human AB serum (Gemini, Calabasas, Calif.), 35-ug/mL transferrin, 5-ug/mL insulin, 2×10^{-5}M ethanolamine, 1 ug/mL palmitic acid, 1 ug/mL linoleic acid, and 1 ug/mL oleic acid (all from Sigma) for 6 days in 25-cm^{2} flasks. Cells are then washed, recultured at a concentration of 1×10^{6}/mL, and restimulated with 2×10^{5}/mL BLCL at day 7. Cells are either prepared for gene transfer on day 8 (early gene transfer) or kept in culture with restimulations weekly at an effector-to-target ratio of 5:1. After the third restimulation, T cells are prepared for gene transfer on day 23 (late gene transfer). A total of 5 IU of IL-2 (Collaborative Biomedical Products) are added for the first time at day 10 to the cultures and 2 to 3 times weekly thereafter. For generation of alloreactive cells, donor T cells are stimulated with fully mismatched allogeneic EBV BLCL. These cells are now routinely generated in the Bone Marrow Transplantation Research Laboratory at MSKCC under the supervision of Dr. G. Koehne, co-investigator.

Gene transfer We have shown (see Progress Report) that EBV-specific CTLs can be easily gene-modified using our strategy developed for primary T-cells. EBV-activated T cells (day 5, day 8, or day 23 of culture) or anti-CD3/anti-CD28-immobilized monoclonal antibody stimulated cells are placed in fibronectin-coated wells according to the technique described by Pollok et al[137] 5 ug/mL of fibronectin fragments (TaKaRa Biomedicals, Shiga, Japan) are coated on nontissue culture treated plates for 2 hours at room temperature in 6-well plates. Plates were blocked with 1% human serum albumin for at least 30 minutes and washed twice with PBS. Cells are plated at a concentration of 10^{6}/mL for 24 hours. Viral supernatant is added and spun for 60 min at 1000 rpm at room temperature. Fifty percent of the supernatant is replaced with fresh medium containing 10% heat-inactivated human AB serum and 10 IU/mL IL-2. Cells will be maintained in culture at a concentration of 10^{6}/mL to 1.5×10^{6}/mL.

Flow cytometric analysis Monitoring of the gene expression of scFv of T lymphocytes will be performed by 2-color flow cytometry using FACScan (Becton Dickinson) by labeling the cells with an anti-scFv-idiotype monoclonal antibody on ice for 45 minutes. FITC-goat anti-rat antibody is added for 15 minutes as secondary antibody. After blocking with normal mouse serum (ICN/CAPPEL, Aurora, Ohio) for 10 minutes, anti-CD3 phycoerythrin (Becton Dickinson) is added for 15 minutes. Cells are washed twice with PBS after each step and before analysis. Phenotyping of specific CTL lines is performed by gating lymphocytes using forward sight scatter and sideward sight scatter. Cells are stained with anti-CD3, anti-CD4, and anti-CD8 for T-cell subpopulations. Although cells have been purified initially for T lymphocytes, the transduced cells will be reanalyzed for the presence of natural killer (NK) cells, defined as CD3-CD16+CD56+, using anti-CD16 and anti-CD56 monoclonal antibodies (Becton Dickinson).

Cell purification by affinity chromatography Gene-modified cells are prepared for purification using affinity purification on MiniMAC columns as described in the previous section.

Cytotoxicity assay Cytolytic activity of effector cells is assayed against ^{51}Cr-labeled targets in standard 4-hour release assays. Target cells include autologous BLCLs, HLA class I mismatched allogeneic BLCLs, and K562 for major histocompatibility complex (MHC)-unrestricted lysis as a parameter for NK cell lysis and PHA blasts. For each donor HLA class I allele, a BLCL expressing the HLA-A and HLA-B allele homozygously can be included to determine the HLA restriction of the EBV-specific CTLs. Briefly, 1×10^{6} target cells are incubated with 3700 kBq ^{51}Cr for 1 hour, washed 3 times, and plated in 96 wells. Cytotoxicity is analyzed using 0.8×10^{5} effector cells: 4×10^{3} target cells per well in a total volume of 200 uL, at an effector-to-target ratio of

20:1. All targets are plated in triplicate. After an incubation of 4 hours, supernatants are harvested and the specific cytotoxicity determined using a microplate scintillation counter (Packard Instruments, Downer's Grove, Ill.). The percentage of specific lysis is calculated as 100%×(experimental release−spontaneous release)/(maximum release−spontaneous release). Maximum release is obtained by adding 100 uL of 5% Triton X-100 to the 100 uL medium containing target cells. Spontaneous release is consistently below 15% of maximum release in all assays.

Comparison of professional killer versus naïve T-lymphocyte in tumor targeting and therapy In order to test if CIR-gene modified professional killer cells are indeed superior in CIR technology, we compare them with CIR-gene modified naïve T-cells as follows:

1. In vitro cytotoxicity (^{51}Cr release and IFN-(release) against tumor cell lines
2. In vivo anti-xenograft activity at various T-cell doses
3. Quantitative difference in homing measured in % injected dose/gm over time (for lymphocytes labeled ex vivo or labeled in vivo) by quantitative PET, tissue counting, immunohistochemistry, and PCR/RT-PCR
4. Qualitative difference in CD4+ T-cells in their ability to recruit either IR-modified T-cells, measured by quantitative PET, tissue counting, immunohistochemistry, and PCR/RT-PCR.
5. Qualitative difference in CD8+ T-cells in their ability to respond to pretargeted CD4+ cells, measured by quantitative PET, tissue counting, immunohistochemistry, and PCR/RT-PCR.

Results We expect the use of professional CTLs to greatly increase the efficiency, specificity, and utility of CIR-modified T cells, as recently reported.[152] Since these cells are selected for EBV with minimal alloreactivity the possibility of using healthy tumor-free allogeneic lymphocytes will increase the chance of full T cell potential in vivo, a close analogy to adoptive allogeneic T cell therapy of EBV-lymphoma. Issues in using autologous T cells, such as immunosuppression by cancer and by chemo-radiotherapy, defective T cell signaling, and tumor contamination are no longer limiting factors. Clearly, allogeneic cells will be rejected by normal hosts even if they are HLA-matched. Fortunately, in patients with solid tumors undergoing high dose therapy, their immune system is often incapacitated, albeit temporarily. In addition, combination of cyclosporin plus mycophenolate mofetil has been quite effective in suppressing graft versus host disease as well as allo-sensitization in preliminary animal studies and early patient trials.[153] We expect the immediate post-chemotherapy period in patients with solid tumors to be relatively immunosuppressed to allow allogeneic T-cells to survive as least for a brief period of weeks to exert its antitumor effect. With immunologic recovery, these gene-modified cells will be eliminated, together with the risk of them becoming cancerous or causing long term autoimmunity. Autologous T cells would have recovered enough by then to allow autologous EBV-specific CTLs to be used. Whether committed EBV-CTLs have shorter life spans than naive T cells after CIR gene-modification remain to be determined. It is likely to expect these preprogrammed professional killer cells (EBV-specific CTL), being preselected in their priming period to express the appropriate repertoire of adhesion molecules (ICAM and selectins), cytokine/interleukins (e.g. IL2, IL4, IL12) and receptors (IL2R, IL7R, IL15R), chemokines (RANTES, IP10) and receptors (CCR5, CXCR3, CCR4), to show better anti-tumor activity than primary T-cells.

Interpretations and Implications The identification of an optimal gene design in the allogeneic setting will increase the likelihood of clinical benefit of CIR technology. The ability to produce large clonal populations of tumor specific T-cells from normal donors for lymphocyte therapy will increase the chance of its successful clinical translation.

TABLE 4

NK92 surface phenotype by FACS	
NK Phenotype	
CD56	+++
CD16	−
CD3	−
CD4	−
CD8	−
CD2	++
CD7	+++
CD25 (IL2Ra)	+
CD122 (IL-2Rb)	++
Cell adhesion molecules (CAM) Ig superfamily	
CD54 (ICAM-1)	+++
CD102 (ICAM-2)	++
CD50 (ICAM-3)	+
Integrins	
B1	
CD29 (B1 integrin B chain)	++
CD49d (VLA-4 a chain)	+++
CD49e (VLA-5 a chain)	−
B2	
CD18 (B2 integrin B chain)	+++
CD11a (LFA-1 a chain)	+++
CD11b (Mac-1 a chain)	−
CD11c (p150/95 a chain)	+
Other CAM	
CD44H	+++
CD44R1	++
CD58 (LFA-3)	+++
NKregulatory Receptors	
CD158a	−
CD158b	−
KIR70	−
CD94	++
NKG2A	+++
Miscellaneous	
CD28	++
CD152 (CTLA-4)	−
CD80	+
CD86	++
C95 (Fas)	+
FasL	−/+
CD69	++
CD34	−
CD43	+++
CD48	+++

TABLE 5

	8H9-scFv-CD28-zeta	
	T-cells	NK92
IL1A	—	—
IL1B	W	—
FIL1(ϵ)	W	W
FIL1	—	—
FIL1(ζ)	Y	Y
IL-1H1	—	—
IL2	—	—

TABLE 5-continued

	8H9-scFv-CD28-zeta	
	T-cells	NK92
IL3	W	W
IL4	W	—
IL5	W	—
IL6	Y	W
IL7	W	Y
IL8	—	W
IL9	Y	Y
IL10	—	W
IL11	Y	Y
IL12A	Y	W
IL12B	—	—
IL13	W	—
IL14	W	W
IL15	Y	Y
IL16	W	W
IL17	W	W
IL17B	W	W
IL17C	—	W
IL17E	Y	Y
IL17F	Y	Y
IL18	—	—
IL19	Y	Y
IL20	—	—
IL21	Y	Y
IL22	Y	Y
IL23A	Y	Y
IL24	W	W
IL26	—	—

TABLE 6

	8H9-scFv-CD28-zeta	
	T-cells	NK92
IL1R1	W	W
IL1R2	W	Y
IL1RL1	—	—
IL1RL2	—	—
IL1RAP	W	W
IL1RAPL1	W	W
IL1RAPL2	—	W
IL1RN	W	—
IL1HY1	—	—
IL2RA	W	W
IL2RB	W	W
IL2RG	Y	Y
IL3RA	—	—
IL4R	—	—
IL5RA	—	—
IL6R	—	W
IL6ST	—	—
IL7R	—	—
IL8RA	—	—
IL8RB	—	—
IL9R	W	W
IL10RA	Y	Y
IL10RB	W	W
IL11RA	W	W
IL12RB1	W	W
IL12RB2	—	W
IL13RA1	W	—
IL13RA2	W	—
IL15RA	W	W
IL17R	Y	Y
IL18R1	—	—
IL18BP	W	Y
IL18RAP	—	—
IL20RA	W	W
IL21R	Y	Y
IL22R	W	Y
IL22RA2	Y	Y

TABLE 7

	8H9-scFv-CD28-zeta	
	T-cells	NK92
ENA-78	W	—
Eotaxin	W	—
GCP-2	Y	Y
I-TAC (IP9) (SCYB11)	—	—
lymphotactin	Y	Y
MCP-1 (SCYA2)	—	—
MCP-2	—	—
MCP-3	—	—
MCP-4	—	—
MDC	Y	Y
MIP-1 delta	W	Y
MIP-1a	Y	Y
MIP-1b	Y	Y
MIP-2 (SCYA21)	W	W
MIP-3a	—	—
MPIF-1	Y	Y
MPIF-2	—	—
P10 (IP 10)	—	—
PARC	W	Y
SCYA19	Y	Y
SCYA5 (RANTES)	Y	Y
SCYB13	Y	Y
SCYC2	Y	Y
SCYE1	W	Y
SDF1	Y	Y
SDF2	Y	Y
TARC (SCYA17)	Y	Y

TABLE 8

	8H9-scFv-CD28-zeta	
	T-cells	NK92
CCR1	W	W
CCR2	Y	Y
CCR3	—	—
CCR4	Y	Y
CCR5	Y	Y
CCR6	W	—
CCR7	W	W
CCR8	W	—
CCR9	W	W
CX3CR1	—	—
CXCR4	W	Y
CXCR5 (BLR1)	—	—
XCR1	Y	Y

TABLE 9

IC50 values (nM) for Octreotide analogs against ^{125}I-SST-14

	SSTR				
Peptide	1	2	3	4	5
Octreotide	>1000	2	187	>1000	22
DTPA-Octreotide	>1000	12	387	>1000	299
DOTA-Octreotide	>1000	14	27	>1000	103
DOTA-Tyr3-Octreotide	>1000	14	880	>1000	393
Y-DOTA-Tyr3-Octreotide	>1000	11	389	>1000	114
Ga-DOTA-Tyr3-Octreotide	>1000	2.5	613	>1000	73
In-DTPA-Octreotide	>1000	22	182	>1000	237
Y-DOTALAN	>1000	23	290	>1000	16
Re0-P829	>1000	2.5	1.5	>1000	2

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SEQUENCE LISTING

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What is claimed is:

1. A method for inducing proliferation in a population of lymphocytes, comprising the steps of:

(a) introducing an expressable gene sequence encoding a chimeric single chain antibody (scFv) coupled to a transmembrane domain and a signaling domain into a lymphocyte, wherein the scFv comprises the heavy and light chain variable regions of monoclonal antibody 8H9, and the transmembrane domain is derived from the transmembrane domain of CD28; and

(b) exposing the lymphocyte to an anti-idiotypic antibody that will bind to the chimeric scfv expressed on the surface of the lymphocyte, thereby inducing proliferation of the lymphocyte.

2. The method of claim **1**, wherein the lymphocyte is a peripheral blood lymphocyte.

3. The method of claim **1**, wherein the lymphocyte is a T cell or NK cell.

4. The method of claim **3**, wherein the T cell is a CD4$^+$ T cell or CD8$^+$ T cell.

5. The method of claim **1**, wherein the lymphocyte is obtained from a cancer patient.

6. The method of claim **1**, wherein the signaling domain is derived from the signaling domain of TCR-ζ chain.

7. The method of claim **1**, wherein the anti-idiotypic antibody is used ex vivo to activate a lymphocyte.

* * * * *

专利名称(译)	制备单链抗体的方法		
公开(公告)号	US8148154	公开(公告)日	2012-04-03
申请号	US12/709848	申请日	2010-02-22
[标]申请(专利权)人(译)	纪念斯隆-凯特琳癌症中心		
申请(专利权)人(译)	斯隆 - 凯特琳癌症研究所		
当前申请(专利权)人(译)	斯隆 - 凯特琳癌症研究所		
[标]发明人	CHEUNG NAI KONG V GUO HONG FEN		
发明人	CHEUNG, NAI-KONG V. GUO, HONG-FEN		
IPC分类号	G01N33/53 C12N15/12 A61K47/48 A61K49/00 C07K16/00 C07K16/18 C07K16/30 C07K16/42		
CPC分类号	A61K47/48623 A61K47/48653 A61K49/0004 A61K49/0006 A61K51/1045 C07K16/00 C07K16/18 C07K16/30 C07K16/3053 C07K16/3084 C07K16/4208 C07K16/4266 A01K2217/05 A61K2039/505 C07K2317/24 C07K2317/565 C07K2317/622 C07K2317/732 C07K2317/77 C07K2319/00 C07K2317/52 A61K47/6865 A61K47/6873		
其他公开文献	US20100226914A1		
外部链接	USPTO		

摘要(译)

本发明提供了从包含不表达靶scFv的细胞的细胞集合中鉴定针对靶抗原的靶单链抗体（scFv）的细胞的方法，包括将细胞集合与抗体结合的步骤。 - 针对靶抗原特异性抗体的亚型，并检测抗独特型与细胞的相互作用（如果有的话），其中相互作用的发生将细胞识别为表达靶scFv的细胞。本发明还提供了制备针对抗原的单链抗体（scFv）的方法，其中克隆的选择是基于这些克隆与适当的抗独特型的相互作用，并且迄今为止如此制备的难以接近的scFv。本发明提供上述方法或其任何组合。最后，本发明提供了这些方法的各种用途。

FIGURE 1