

Chimeric mouse-human IgG1 antibody that can mediate lysis of cancer cells

(immunoglobulin domain cDNA/DNA transfection/tumor antigen/complement-dependent cytotoxicity/antibody-dependent cellular cytotoxicity)

ALVIN Y. LIU*[†], RANDY R. ROBINSON*, KARL ERIK HELLSTRÖM^{‡§}, E. DAVID MURRAY, JR.*[¶],
C. PAUL CHANG*, AND INGEGERD HELLSTRÖM^{‡||}

*International Genetic Engineering, Inc., 1545 17th Street, Santa Monica, CA 90404; [†]Oncogen, 3005 First Avenue, Seattle, WA 98121; and Departments of [‡]Pathology and ^{||}Microbiology, University of Washington Medical School, Seattle, WA 98195

Communicated by Paul D. Boyer, January 28, 1987 (received for review December 22, 1986)

ABSTRACT A chimeric mouse-human antibody has been created that recognizes an antigen found on the surface of cells from many carcinomas. Immunoglobulin constant (C) domains of the mouse monoclonal antibody L6, C_{γ2a} and C_κ, were substituted by the human C_{γ1} and C_κ by recombining cDNA modules encoding variable or C domains. The cDNA constructs were transfected into lymphoid cells for antibody production. The chimeric antibody and mouse L6 antibody bound to carcinoma cells with equal affinity and mediated complement-dependent cytotoxicity. In the presence of human effector cells, the chimeric antibody gave antibody-dependent cellular cytotoxicity at 100 times lower concentration than that needed for the mouse L6 antibody. The chimeric antibody, but not the mouse L6 antibody, is effective against a melanoma line expressing small amounts of the L6 antigen. The findings point to the usefulness of the chimeric antibody approach for obtaining agents with strong antitumor activity for possible therapeutic use in man.

The presence of tumor-associated antigens at the cell surface is a characteristic of many cancers. Since these antigens are either absent or found in much lower amounts in normal cells, it should be possible to use antibodies for targeting of tumors. A sizeable collection of relatively tumor-specific monoclonal antibodies (mAb) of mouse origin is available (1). Some of these mAb possess tumoricidal activity in the presence of human effector cells [antibody-dependent cellular cytotoxicity (ADCC)] or serum [complement-dependent cytotoxicity (CDC)] (2, 3). It has been shown (4) that partial tumor regression can be achieved when mAb possessing such functional activity are given to patients. One complication preventing repeated use of mouse mAb in man is that they are immunogenic. Furthermore, mouse mAb may interact less efficiently with human effector cells to mediate tumor destruction.

A method made possible by recombinant DNA technology was chosen to generate chimeric mouse-human antibodies. It entails the replacement of the mouse constant (C) domain regions with the corresponding human equivalents (5-7). In principle, antibody molecules obtained by this approach should retain their specificity for antigen and thus their usefulness for targeting, be much less immunogenic to man, and perhaps have increased antitumor activity.

The mouse mAb L6 [IgG2a(κ)] binds to a carbohydrate antigen found at the surface of cells from human carcinomas of the lung, breast, colon, and ovary (8). L6 can mediate CDC with human complement or ADCC with human effector cells (2). mAb L6 may thus be of use for tumor targeting, either in its native form or after conjugation of anticancer agents.

In this study we have generated a mouse-human chimeric L6 antibody in which the mouse constant domains C_{γ2a} and C_κ are substituted by the human C_{γ1} and C_κ. First, the cDNAs encoding the immunoglobulin genes were isolated. Next, restriction enzyme recognition sites were created in the cDNA sequences at the V/C junction (where V stands for variable) (9) by *in vitro* mutagenesis using oligodeoxynucleotides (10). The chimeric cDNAs thus constructed were then introduced into lymphoid cells by DNA transfection. The chimeric antibody isolated from the transfectants was compared with the mouse L6 for effector functions.

MATERIALS AND METHODS

DNA Transfection of Mouse Sp2/0 Lymphoid Cells. Expression plasmid pING2114 (50 μg), linearized at a unique site (*Aat* II) in the nonessential bacterial region (see Fig. 3A), was transfected into 10⁷ mouse Sp2/0 cells (CRL 1581, ATCC) by electroporation (11, 12). Transformants were selected in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% (vol/vol) fetal bovine serum (HyClone, Logan, UT) and G418 at 0.8 mg/ml (GIBCO). The transfection frequency was between 10⁻⁵ and 10⁻⁴. Human antibody in the medium was detected by ELISA (13).

Isolation of Chimeric Antibody. Antibody-producing cells were grown to a density of 10⁶ cells per ml and then shifted to serum-free DMEM 24 hr before harvest. Antibody secreted by the cells was concentrated by ultrafiltration, then chromatographed on a DEAE-cellulose column equilibrated in 40 mM NaCl/10 mM sodium phosphate, pH 8.0. The antibody in the flow-through was further purified to apparent homogeneity on protein A-Sepharose (14). For production of ascites fluid, 10⁶ cells were injected into pristane-primed BALB/c mice. The chimeric antibody was purified by anti-human IgG-Sepharose chromatography (14).

Functional Tests of the Chimeric L6 Antibody. The following tests were included: (i) measurement of antibody binding to target cells, either positive or negative for reactivity with the mouse L6; (ii) competitive inhibition of binding of L6 to these cells; (iii) assays for CDC and ADCC. The binding tests were performed using a Coulter model EPIC-C cell sorter (8). The assays for CDC and ADCC were carried out on ⁵¹Cr-labeled target cells (2, 3) that were exposed to antibodies and human serum or peripheral blood leukocytes over a 4-hr period.

Abbreviations: V, variable; C, constant; J, joining; mAb, monoclonal antibody(ies); CDC, complement-dependent cytotoxicity; ADCC, antibody-dependent cellular cytotoxicity; SV40, simian virus 40; H, heavy.

A L6 V_H

met asp trp leu

C₂₃AGTTTGTCTTAAGGCACCACTGAGCCCAAGTCTTAGACATCATG GAT TGG CTG

BAL31 del. Afl II
GTCGACTCT

Sal I leader peptide FR1
trp asn leu leu phe leu met ala ala ala gln ser ala gln ala gln
TGG AAC TTG CTA TTC CTG ATG GCA GCT GCC CAA AGT GCC CAA GCA CAG

ile gln leu val gln ser gly pro glu leu lys lys pro gly glu thr
ATC CAG TTG GTG CAG TCT GGA CCT GAG CTG AAG AAG CCT GGA GAG ACA

val lys ile ser cys lys ala ser gly tyr thr phe thr^{FR1}asn^{CDR1} tyr gly
GTC AAG ATC TCC TGC AAG GCT TCT GGG TAT ACC TTC ACA AAC TAT GGA

Bgl II
CDR1^{FR2}
met asn^{FR2} trp val lys gln ala pro gly lys gly leu lys trp met gly^{FR2}
ATG AAC TGG GTG AAG CAG GCT CCA GGA AAG GGT TTA AAG TGG ATG GGC

Aha III
CDR2
trp ile asn thr tyr thr gly gln pro thr tyr ala asp asp phe lys
TGG ATA AAC ACC TAC ACT GGA CAG CCA ACA TAT GCT GAT GAC TTC AAG

Nde I
CDR2^{FR3}
gly arg phe ala phe ser leu glu thr ser ala tyr thr ala tyr leu
GGA CGG TTT GCC TTC TCT TTG GAA ACC TCT GCC TAC ACT GCC TAT TTG

gln ile asn asn leu lys asn glu asp met ala thr tyr phe cys ala
CAG ATC AAC AAC CTC AAA AAT GAG GAC ATG GCT ACA TAT TTC TGT GCA

FR3^{CDR3} CDR3^{FR4}
arg phe ser tyr gly asn ser arg tyr ser asp tyr^{FR3} trp gly gln gly
AGA TTT AGC TAT GGT AAC TCA CGT TAC TCT GAC TAC TGG GGC CAA GGC

Dsp2.2
JH2
thr thr leu thr val ser ser ala lys thr thr ala pro ser
ACC ACT CTC ACA GTC TCC TCA GCC AAA ACA ACA GCC CCA TCG

GC AG G MJH2Apa I

B L6 V_K

leader peptide

met asp phe gln val gln ile phe ser phe leu leu

C₉CCCCAAGACAAAATG GAT TTT CAA GTG CAG ATT TTC AGC TTC CTG CTA

GTC 5'Sal I

ile ser ala ser val ile met ser arg gly^{FR1} gln ile val leu ser gln
ATC AGT GCT TCA GTC ATA ATG TCC AGA GGA CAA ATT GTT CTC TCC CAG

ser pro ala ile leu ser ala ser pro gly glu lys val thr leu thr
TCT CCA GCA ATC CTG TCT GCA TCT CCA GGG GAG AAG GTC ACA TTG ACT

FR1^{CDR1} CDR1^{FR2}
cys arg ala ser ser ser val ser phe met asn^{FR2} trp tyr gln gln lys
TGC AGG GCC AGC TCA AGT GTA AGT TTC ATG AAC TGG TAC CAG CAG AAG

Kpn I
pro gly ser ser pro lys pro trp ile tyr^{FR2} ala thr ser asn leu ala
CCA GGA TCC TCC CCC AAA CCC TGG ATT TAT GCC ACA TCC AAT TTG GCT

Bam HI
CDR2^{FR3}
ser glu phe pro gly arg phe ser gly glu trp ser gly thr ser tyr
TCT GAG TTC CCT GGT CGC TTC AGT GGC GAG TGG TCT GGG ACC TCT TAC

ser leu ala ile ser arg val glu ala glu asp ala ala thr tyr tyr
TCT CTC GCA ATC AGC AGA GTG GAG GCT GAA GAT GCT GCC ACT TAT TAC

FR3^{CDR3} CDR3^{FR4}
cys gln gln trp asn ser asn pro leu thr phe gly ala gly thr lys
TGC CAG CAG TGG AAT AGT AAC CCA CTC ACG TTC GGT GCT GGG ACC AAG

J_K5-
leu glu leu lys

FIG. 1. Nucleotide sequences and predicted amino acid sequences of the L6 V_H (A) and V_K (B). The framework (FR) and complementarity determining region (CDR) segments are indicated. The diversity (D) segment in V_H is underlined. Circles above the amino acid residues indicate that these residues matched to those obtained from peptide sequencing. The V_H sequence is present in plasmid pH3-6a. The C₂₃ at the 5' end was removed by BAL-31 nuclease digestion. The resultant DNA sequence at the 5' end is shown below the first line. An *Apa* I site was introduced by the oligonucleotide primer MJH2ApaI. The V_K sequence is present in plasmid pL3-12a. The C₁₃ at the 5' end was removed by oligonucleotide-mediated mutagenesis.

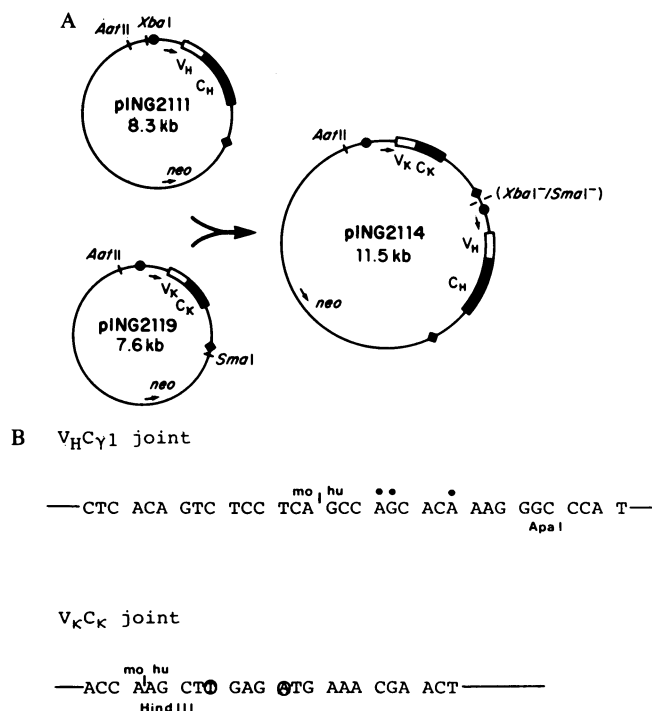


FIG. 3. (A) Expression plasmids. pING2111 is the heavy-chain and pING2119 is the light-chain expression plasmid. They were used to construct pING2114, a two-gene plasmid. Solid circles, mouse heavy-chain immunoglobulin gene enhancer; small arrows, SV40 early promoter; diamonds, bidirectional SV40 transcription termination/polyadenylation signals. (B) Nucleotide changes made in the V/C junction. Dotted residues in the $V_H C_{\gamma 1}$ junction were introduced by oligonucleotide-mediated mutagenesis. They are silent changes. Circled residues in the $V_K C_K$ junction are residues contributed by the human cDNA module to the mouse V_K gene.

Fig. 6 shows ADCC tests with cells from two cell lines. At a ratio of 100:1 human peripheral blood leukocytes to the colon carcinoma line C-3347 cells, the chimeric L6 killed a greater fraction of the target cells (a maximum of 98% versus 63%) and gave 50% ADCC at 100 times lower concentration than the mouse L6 (0.01 $\mu\text{g/ml}$ versus 1 $\mu\text{g/ml}$, Fig. 6A). Significant ADCC of C-3347 cells (24% as compared to 3% lysis with lymphocytes alone) was observed down to a 3:1 ratio of effector cells to target cells when the chimeric L6 (at 2.5 $\mu\text{g/ml}$) was used (Fig. 6B). Cell killing was specific because ADCC was not observed with the following three cell lines lacking detectable L6 antigens: B-cell lines DHL-10 (Fig. 6C) and T51 (data not shown) and the T-cell line HSB-2

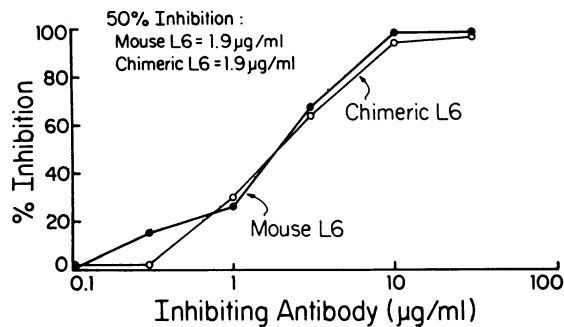


FIG. 4. Comparison between chimeric and standard mouse L6 in antibody inhibition assays, performed by fluorescence-activated cell sorting. C-3347 cells were incubated with the blocking antibodies

Table 1. Binding of chimeric L6 and mouse L6 antibodies to cell lines used as targets for functional assays

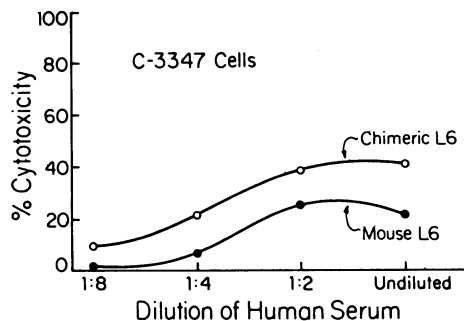
Antibody	Antibody concentration, $\mu\text{g/ml}$	Binding ratio*	
		GAM	GAH
Human colon carcinoma line C-3347			
Mouse L6	30	38	4
	10	49	4
	3	40	3
Chimeric L6 (ascites)	30	2	108
	10	2	84
	3	1	42
Chimeric L6 (cell culture)	30	1	105
	10	1	86
	3	1	44
Human melanoma line M-2669 (clone 13)			
Mouse L6	30	7	NT
	10	3	NT
	3	1	NT
Chimeric L6 (cell culture)	30	NT	4
	10	NT	2
	3	NT	1
Human T-cell line HSB-2			
Mouse L6	10	1	1
	10	1	1
	10	1	1

*The binding ratio is the number of times a test sample is brighter than a control sample when treated with GAM (fluorescein isothiocyanate-conjugated goat anti-mouse immunoglobulin) or with GAH (fluorescein isothiocyanate-conjugated goat anti-human immunoglobulin). For example, a ratio of 1 means that the test sample is as bright as the control; a ratio of 2 means that the test sample is twice as bright as the control. NT, not tested.

(data not shown). Efficacy of the chimeric L6 was further demonstrated by its ability to lyse M-2669 melanoma cells (35% at 10 $\mu\text{g/ml}$, 27% at 0.1 $\mu\text{g/ml}$); the mouse L6 had no effect on these cells (9% at 10 $\mu\text{g/ml}$, as compared to 10% lysis with lymphocytes alone, *cf.* Table 1).

DISCUSSION

The mouse mAb L6 recognizes a carbohydrate antigen present in abundance in a variety of carcinomas. Normal tissues express only trace amounts of the antigen (8). Based on this specificity there is justification in considering L6 for cancer treatment with the mAb used either alone (2) or as a carrier of anticancer agents. However, the immunogenicity of mouse L6 mAb in man is a disadvantage for its sustained use in patients, and its functional activity (ADCC and CDC) may be insufficient to effect optimal tumor destruction at the



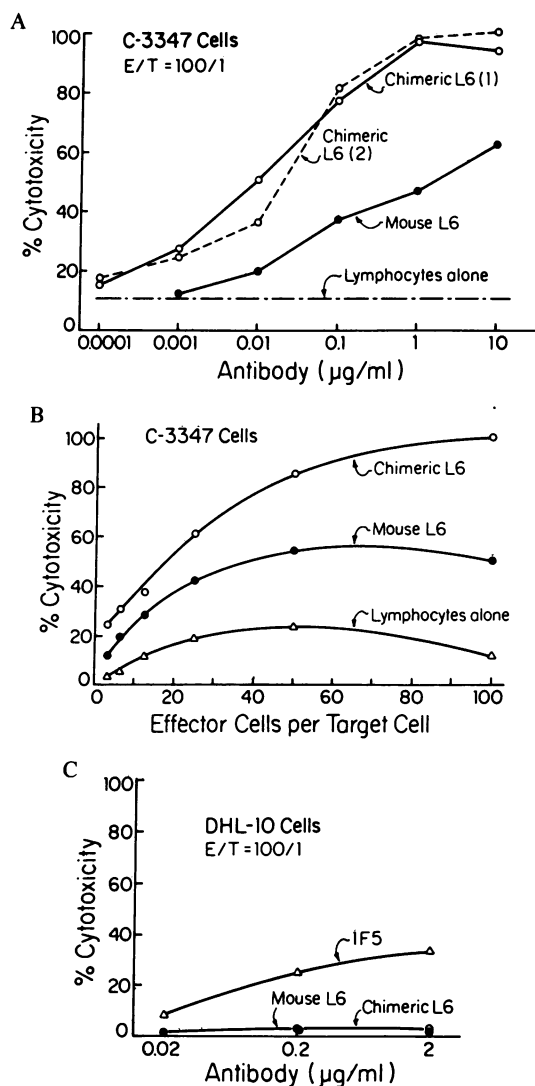


FIG. 6. (A) Titration of chimeric and mouse L6 antibodies in ADCC assays with human peripheral blood leukocytes. E/T, effector-target cell ratio. Two preparations of chimeric L6 were used. (B) Titration of human peripheral blood leukocyte effector cells mediating ADCC in the presence of antibodies (2.5 $\mu\text{g/ml}$). (C) Titration of L6 (chimeric and mouse) in ADCC assays on the DHL-10 T-cell line. 1F5 is a mouse mAb that recognizes the DHL-10 cells.

concentrations that can be attained in tumors after intravenous administration.

It is estimated that a major immunogenic site resides in the C_H2 region (23) of the IgG molecule. As one approach to decrease this problem, one could generate chimeric mouse-human antibodies thereby replacing the immunogenic C domains of the mouse immunoglobulins with those of human immunoglobulins. We did this using cDNA rather than cloned genomic DNA (24, 25). We show here that this is a useful approach for producing chimeric antibody. In cell line 3E3 and its subclones close to 1 $\mu\text{g/ml}$ of IgG1 protein was detected.

The chimeric antibody was found to bind to tumor cells as well as the mouse L6 antibody. The chimeric antibody was much more efficient than L6 in ADCC assays, killing a greater fraction of target cells at a concentration lower by a factor of 100. Furthermore, the chimeric L6 killed cells from a melanoma line that was refractory to ADCC by the mouse

the functional attributes of chimeric L6, should make it a strong candidate for therapeutic trials. Some of the antibodies induced in man to mouse mAb were directed to idiotypic determinants (26, 27). It remains to be seen whether the immunogenicity of those determinants of the chimeric L6 will be different from that of the mouse L6.

The advantage of the cDNA approach lies in the ease with which immunoglobulin gene cDNAs can be isolated. The technology used for the present work should make it possible to convert many other mouse mAb to chimeric antibodies with improved antitumor activity via ADCC and CDC mechanisms. The chimeric antibodies will augment the relatively few human mAb currently used in the treatment of cancer (28).

We thank Cathy Shapiro, Phil Mack, Phil Mixter, Pam Smith, Susan Azemove, Grethe Lovold, and Pat McGowan for excellent technical assistance. We also thank Randy Wall for discussion, and Randy Wall, Carol Hersh, Arup Sen, Gary Wilcox, Perry Fell, Jeff Ledbetter, Peter Linsley, and Erik Milner for useful comments on the manuscript. The work was supported by INGENE and ONCOGEN.

- Hellström, K. E. & Hellström, I. (1985) in *Monoclonal Antibodies for Cancer Detection and Therapy*, eds. Baldwin, R. S. & Byers, V. S. (Academic, New York), pp. 17-51.
- Hellström, I., Beaumier, P. L. & Hellström, K. E. (1986) *Proc. Natl. Acad. Sci. USA* 83, 7059-7063.
- Hellström, I., Brankovan, V. & Hellström, K. E. (1985) *Proc. Natl. Acad. Sci. USA* 82, 1499-1502.
- Houghton, A. N., Mintzer, D., Cordon-Cardo, C., Welt, S., Fliegel, B., Vadhan, S., Carswell, E., Melamed, M. R., Oettgen, H. F. & Old, L. J. (1985) *Proc. Natl. Acad. Sci. USA* 82, 1242-1246.
- Morrison, S. L., Johnson, M. J., Herzenberg, L. A. & Oi, V. T. (1984) *Proc. Natl. Acad. Sci. USA* 81, 6851-6855.
- Boulianne, G. L., Hozumi, N. & Shulman, M. J. (1984) *Nature (London)* 312, 643-646.
- Neuberger, M. S., Williams, G. T., Mitchell, E. B., Jouhal, S. S., Flanagan, J. G. & Rabbitts, T. H. (1985) *Nature (London)* 314, 268-270.
- Hellström, I., Horn, D., Linsley, P., Brown, J. P., Brankovan, V. & Hellström, K. E. (1986) *Cancer Res.* 46, 3917-3923.
- Liu, A. Y., Mack, P. W., Champion, C. I. & Robinson, R. R., *Gene*, in press.
- Zoller, M. J. & Smith, M. (1982) *Nucleic Acids Res.* 10, 6487-6500.
- Potter, H., Weir, L. & Leder, P. (1984) *Proc. Natl. Acad. Sci. USA* 81, 7161-7165.
- Toneguzzo, F., Hayday, A. C. & Keating, A. (1986) *Mol. Cell. Biol.* 6, 703-706.
- Mixter, P. F., Wu, S. V., Studnicka, G. M. & Robinson, R. R. (1986) *J. Immunol. Methods* 91, 195-203.
- Johnstone, A. & Thorpe, R. (1982) *Immunocytochemistry in Practice* (Blackwell Scientific, Oxford), pp. 27-76.
- Gubler, U. & Hoffman, B. J. (1983) *Gene* 25, 263-269.
- White, B. A. & Bancroft, F. C. (1982) *J. Biol. Chem.* 257, 8569-8572.
- Nobrega, F. G., Dieckmann, C. L. & Tzagoloff, A. (1983) *Anal. Biochem.* 131, 141-145.
- Legerski, R. J., Hodnett, J. L. & Gray, H. B., Jr. (1978) *Nucleic Acids Res.* 5, 1445-1463.
- Messing, J. (1983) *Methods Enzymol.* 101, 20-78.
- Okayama, H. & Berg, P. (1983) *Mol. Cell. Biol.* 3, 280-289.
- Southern, P. J. & Berg, P. (1982) *J. Mol. Appl. Genet.* 1, 327-341.
- Mulligan, R. C. & Berg, P. (1981) *Proc. Natl. Acad. Sci. USA* 78, 2072-2076.
- Novotný, J., Handschumacher, M. & Haber, E. (1986) *J. Mol. Biol.* 189, 715-721.
- Sun, L. K., Curtis, P., Rakowicz-Szulczynska, E., Ghayeb, J., Morrison, S. L., Chang, N. & Koprowski, H. (1986) *Hybridoma* 5 Suppl. 1, S17-S20.
- Sahagan, B. G., Dorai, H., Saltzgeber-Muller, J., Toneguzzo, F., Guindon, C. A., Lilly, S. P., McDonald, K. W., Morrissey, D. V., Stone, B. A., Davis, G. L., McIntosh, P. K. & Moore, G. P. (1986) *J. Immunol.* 137, 1066-1074.
- Goodman, G. E., Beaumier, P. L., Hellström, I., Fernyhough, B. & Hellström, K. E. (1985) *J. Clin. Oncol.* 3, 340-352.
- Koprowski, H., Herlyn, D., Lubeck, M., DeFreitas, E. & Sears, H. F. (1984) *Proc. Natl. Acad. Sci. USA* 81, 216-219.