The Open Reading Frames in the 3′ Long Terminal Repeats of Several Mouse Mammary Tumor Virus Integrants Encode Vβ3-specific Superantigens

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Summary

Mice expressing the minor lymphocyte stimulation antigens, Mls-1[a], -2[a], or -3[a], singly on the B10.BR background have been generated. Mls phenotypes correlate with the integration of mouse mammary tumor viruses (MTV) in the mouse genome. The open reading frames within the 3′ long terminal repeats of the integrated MTVs 1, 3, 6, and 13 encode Vβ3-specific superantigens. Sequence data for these viral superantigens is presented, indicating that it is the COOH-terminal portion of the viral superantigen that interacts with the T cell receptor Vβ element.

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A number of murine alloantigens have been described that, in combination with MHC class II products, stimulate T cells bearing particular Vβ elements (1–8). These alloantigens have been termed superantigens (9). Mice expressing such superantigens delete thymocytes bearing reactive Vβ elements during development in the thymus (10). This clonal elimination of thymocytes maintains self-tolerance by preventing mature self-reactive T cells from reaching the periphery.

The analysis of peripheral expression of T cells bearing particular Vβ elements has recently facilitated the mapping of several of these superantigens to particular chromosomal locations. Woodland et al. (11, 12) found no recombinants between the gene encoding a superantigen (*Etc*-1), which causes deletion of Vβ11- and Vβ5.2-bearing T cells, and a mouse mammary tumor virus (MTV)[1] integrant (*Mtv*-9) on chromosome 12. In addition, the genes for several other endogenous mouse superantigens map to the same chromosomal regions as MTV integrants (4, 13, 14). In the past, however, some recombinants between the genetic locations of mouse endogenous superantigens and *Mtv*s had been reported in the AKXD and BXD recombinant inbred mice. Suspecting that these reported recombinants may have been mistyped, Frankel et al. (15) retyped the collection of AKXD and BXD mice for MTV integrants and, after correcting previous typings, found perfect correlation between the expression of several superantigens and presence of particular MTV integrants in these mice. Thus, these investigators suggested that MTV integrants themselves code for the endogenous mouse superantigens. Independently, Dyson et al. (16) arrived at the same conclusion after mapping several ligands that delete Vβ11$^+$ T cells.

Recently, we have shown that the infectious milk-borne MTV carried by C3H/HeJ mice codes for a superantigen that interacts with T cells bearing Vβ14 and -15 (17, 18). Furthermore, transfection experiments have shown that it is the product of the open reading frame (ORF) within the 3′ long terminal repeat (LTR) of the C3H MTV that confers the ability to interact with TCR in a Vβ-specific manner (18). Acha-Orbea et al. (19) have shown, using a transgenic model, that the ORF of the infectious MTV transmitted in the milk of GR mice also causes deletion of Vβ14$^+$ thymocytes. We have suggested the name viral superantigen (vSAG) for these ORF genes.

In this study, we have used mice expressing Mls-1[a] -2[a], or -3[a] singly on the B10.BR background to demonstrate conclusively the correlation between the expression of these Mls phenotypes and the presence of *Mtv*-7, -1, and -6 (vSAG-7, -1, and -6), respectively. Transfection experiments showed that *Mtv*-1 and *Mtv*-3 vSAGs encode Vβ3-specific superantigens. The sequences presented here for the MTV vSAGs with Vβ3 specificity (*Mtv*-1, -3, -6, and -13) strengthen the hypothesis that it is the COOH-terminal region of the vSAG that interacts with the TCR Vβ.

[1] *Abbreviations used in this paper:* LTR, long terminal repeat; MTV, mammary tumor virus; ORF, open reading frame; VSAG, viral superantigens.

Materials and Methods

Mice. Mice were generally purchased from The Jackson Laboratory (Bar Harbor, ME). Mice carrying Mls-1[a], Mls-2[a], or Mls-3[a] on the B10.BR background were bred in our own facility.

Flow Cytometric Analyses. Nylon wool–purified, peripheral blood and lymph node T cells were analyzed for expression of Vβ3 and Vβ6 as outlined previously (9). T cells were stained with biotinylated KJ25 (anti-Vβ3; reference 4) or RR4-7 (anti-Vβ6; reference 20) followed by PE-streptavidin (Tago Inc., Burlingame, CA). Two-color analyses of TCR Vβ expression and CD4 and/or CD8 used directly fluoresceinated GK1.5 (21) and 53.6.71 (22), respectively.

Southern Analyses. Liver or tail DNA was digested with PvuII, subjected to electrophoresis on 0.7% agarose gels, and transferred to nitrocellulose as described by Maniatis et al. (23). Filters were hybridized with a MTV LTR probe. The probe was an EcoRI-BamHI fragment of pTZ18R-ORF (18), derived from the milk-borne C3H MTV (kindly provided by Dr. John Majors, Washington University School of Medicine, St. Louis, MO). The probe was labeled by random priming (24). Filters were washed with two final washes with 0.1% SSC, 0.1% SDS at 58°C for 30 min.

PCR Amplification, Cloning, and Sequencing of MTV vSAGs. Oligonucleotide primers specific for C3H MTV vSAG (5′ sense, GGGAATTCTCGAGATGCCGCGCCTGCAG; and 3′ antisense, GGGGATCCAACTAACTTAAACCTTGG) were used to amplify the vSAGs from PvuII-digested genomic DNA from DBA/2 and C58 mice. The DNA was separated on a 0.7% agarose gel and gel pieces corresponding to the 3′ LTRs of *Mtv*-1, -6, and -13 from DBA/2 and *Mtv*-3 from C58 (Fig. 1) were excised. DNA purified using Geneclean (Bio 101 Inc., La Jolla, CA) was subjected to PCR amplification using a thermocycler (Cetus Corp., Norwalk, CT) and the following amplification conditions: 95°C melting, 50°C, annealing, and 72°C extension, each for 2 min. The amplified products were restricted with BamHI and EcoRI and cloned into pTZ18R. Multiple clones were sequenced by the chain termination method (25) using the Sequenase kit (United States Biochemical Corp., Cleveland, OH).

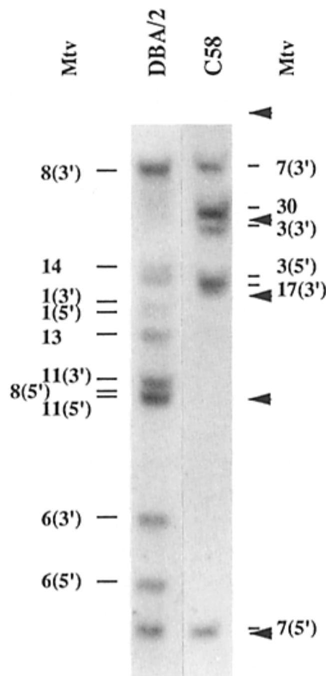

Figure 1. Southern blot of PvuII-digested DNA from DBA/2 and C58 mice. The filter was hybridized with a probe derived from C3H exogenous MTV LTR. Arrow heads designate molecular weight markers of 23.5, 9.4, 6.6, 4.3, and 2.3 kb.

Transfection. The vSAGs of *Mtv*-1 and *Mtv*-3 were subsequently cloned into the eukaryotic expression vector pBDWMCβ2 (26). In case other retroviral products were necessary to ensure high expression of the vSAG products, the vSAG constructs were cotransfected with pUVH, a plasmid containing the 5′ sequences of the endogenous C3H provirus *Mtv*-1 and the 3′ sequences of the milk-borne exogenous C3H MTV (27). These plasmids were linearized with XbaI and SalI respectively, and were transfected into the B cell line CH12.1 (28) by electroporation. Transfectants were selected with G418.

Stimulation Assays. Transfectants were screened for their ability to stimulate T cell hybrids expressing Vβ3 (K25-49.16 and K25-59.6; reference 4) and Vβ7 (KOX7-6.6; reference 18). 10^5 B cell transfectants were cultured with 10^5 T cell hybrids. Lymphokine production was assayed after 24 h using the indicator cell line HT-2 (29).

Results and Discussion

Endogenous Mouse Superantigens Map to MTV Integration Sites. Previously published analysis of the progeny of a (C3H/HeJ × B10.BR)F_1 × B10.BR backcross has shown that C3H/HeJ mice express two Vβ3-specific superantigens, Mls-2[a] and Mls-3[a] (30). The progeny that expressed Mls-2[a] or Mls-3[a] were further backcrossed on to the B10.BR background. For each generation, the offspring were screened for Vβ3 expression and the mice expressing low levels of V$\beta 3^+$ peripheral blood T cells were used as breeders. Expression of Mls-2[a] causes partial deletion of V$\beta 3^+$ T cells, while Mls-3[a] causes complete deletion of these cells (Table 1; and reference 30). Fig. 2 shows a Southern blot of genomic DNA from the backcrossed mice hybridized with a probe derived from C3H exogenous MTV LTR. Mice expressing the Mls-2[a] phenotype carried *Mtv*-1, while the Mls-3[a] mice carried *Mtv*-6. This is a formal demonstration that the Mls-2[a] phenotype correlates with the presence of *Mtv*-1, a possibility suggested by Frankel et al. (15).

Concurrently, we have backcrossed the Mls genes of CBA/J on to the B10.BR background. Deletion of V$\beta 6^+$ T cells was used as a marker for Mls-1[a] expression (3) and the absence of Vβ3-bearing cells was taken to indicate the presence of another Mls gene. Mls-1[a] expression correlates with the

Table 1. *Vβ3-specific Deletion of T Cells by Endogenous Mouse Superantigens*

	Source of Mls genes	Percent V$\beta 3^+$ lymph node T cells
B10.BR		3.5
CBA/J		0.1
C3H/HeJ		0.1
B10.BR-Mls-3[a](F6)	CBA/J	0.1
B10.BR-Mls-2[a](F8)	C3H/HeJ	0.5
B10.BR-Mls-3[a](F7)	C3H/HeJ	0.1

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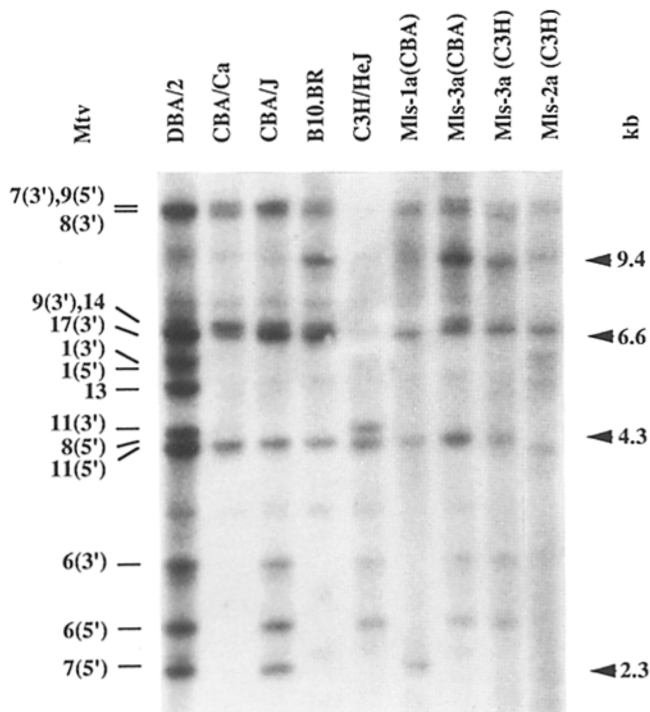

Figure 2. Endogenous mouse superantigens map to MTV integration sites. A Southern blot of PvuII-digested DNA from inbred and recombinant mouse strains was hybridized with a probe derived from C3H exogenous MTV LTR. The higher molecular weight bands for C3H/HeJ are faint due to partial degradation of the DNA sample. Mls-1a(CBA) designates B10.BR-Mls-1ᵃ (F6), Mls-3a(CBA) designates B10.BR-Mls-3ᵃ(F6), Mls-3a(C3H) designates B10.BR-Mls-3ᵃ(F6), and Mls-2a(C3H) designates B10.BR-Mls-2ᵃ(F7). Assignments are made for the MTV integrants that are known to be present in these mouse strains.

presence of *Mtv*-7 on chromosome 1 (Fig. 2; and reference 15). It has previously been reported that, unlike C3H/HeJ and DBA/2, CBA/J carries only one Vβ3-specific superantigen (31–33). The expression of this superantigen correlates with the presence of *Mtv*-6 (Table 1 and Fig. 2), and it is therefore termed Mls-3ᵃ.

Four Different MTV Integrants Encode Vβ3-specific Superantigens. Analyses of Vβ3 expression in RI mice of the AKXD and BXD series suggested that DBA/2 mice carry at least two genes encoding Vβ3-specific superantigens (4, 14); one mapping to chromosome 4 and a second to chromosome 16. Reanalysis of these data and the MTV integration sites for the RI strains suggested that DBA/2 mice actually carry three Vβ3-specific superantigens, Mls-2ᵃ, Mls-3ᵃ, and one other, mapping to the retroviral integrants *Mtv*-1, *Mtv*-6, and *Mtv*-13 on chromosomes 7, 16, and 4, respectively (15). There is, however, evidence for yet another endogenous mouse superantigen that reacts with T cells bearing Vβ3. Several strains, including C58, NZB, NOD, and CE, have low levels of Vβ3 expression but do not carry *Mtv*s 1, 6, or 13 (4, 15, 34). Fairchild et al. (35) have recently demonstrated, by analyzing the progeny of a (B10.S(9R) × NOD)F_1 × B10.BR backcross, that the Vβ3 deletion phenotype of NOD mice correlates with the presence of *Mtv*-3 on chromosome 11. To study the relationship between these four Vβ3-specific MTV integrants, we cloned and sequenced the 3′ LTV vSAGs of these viruses as described in Materials and Methods.

The *Mtv*-1 vSAG sequence from DBA/2 (Fig. 3) differed from the published sequence for *Mtv*-1 from C3H (36) at two positions; first by a C-G mutation in codon 55 resulting in a Pro-Ala substitution, and second, by the insertion of a single base at the third position of codon 315. The resulting protein encoded by this ORF is therefore three amino acids longer. Since *Mtv*-1 in C3H mice interacts with Vβ3⁺ T cells, it suggests that the terminal three amino acids of the *Mtv*-1 vSAG in DBA/2 are not required for T cell stimulation or, alternatively, it is possible that the published sequence for C3H *Mtv*-1 may be wrong.

The *Mtv*-6 and *Mtv*-13 vSAGs were amplified from DNA from RI strains BXD-8 and BXD-1, respectively. Each of these RI strains carries only one MTV integrant that encodes a Vβ3-specific superantigen derived from DBA/2 (37). The *Mtv*-1 and *Mtv*-6 vSAG genes only differ by eight nucleotides (Fig. 3); however, it is striking that their amino acid sequences are identical. This finding is surprising, since it is known that the products of these genes differ in the efficiency with which they cause T cell deletion. Mice bearing *Mtv*-6 completely delete Vβ3⁺ T cells, while *Mtv*-1 expression results in only partial deletion of these T cells (4, 14, 15, 30). Perhaps differences elsewhere in the MTV genomes, or the different chromosomal integration sites, cause expression of the various Vβ3-specific MTV superantigens in different tissues or at different levels.

The *Mtv*-13 vSAG differs from that of *Mtv*-1 by seven nucleotides; five of these differences are silent and the other two result in amino acid differences at positions 28 and 45 (Fig. 3). The similarity of the three MTV integrants encoding Vβ3-specific superantigens derived from DBA/2 mice may be due to the insertion of similar MTVs at distinct sites in the mouse genome, on chromosomes 16, 4, and 7, or alternatively, it may be due to the transfer of the provirus from one chromosomal location to another with subsequent point mutations.

The sequence of *Mtv*-3 vSAG from C58 differs from the *Mtv*-1 vSAG by 10 amino acids (Fig. 3). All these residues, except Thr at position 317, have been found in other MTV vSAGs. Similar relationships between other MTV vSAGs can be observed in other published sequences (38–41) (Fig. 4). On the whole, amino acids found substituted in one vSAG can also be found in other ORFs, suggesting the occurrence of multiple recombination events; possibly by recombination between milk-borne infectious viruses, or alternatively, by gene conversion between the integrated proviruses.

Comparisons of the published sequences of vSAGs from the exogenous C3H MTV (39) and integrated MTVs 1, 8, 9, and 11 (36, 40, 41), led us to speculate that the 30 or so amino acid residues at the COOH-terminal of the vSAGs were responsible for the Vβ specificity (18). This was supported by the demonstration by Acha-Orbea et al. (19) that transgenic mice expressing a variant of the C3H MTV did not delete Vβ14⁺ T cells, whereas the wild-type virus, which differs from the variant at amino acids 288–315 of the ORF, clearly caused the deletion of Vβ14-bearing T cells.

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          1                         10                            20                            30                            40
MTV1   ATGCCGCGCCTGCAGCAGAAATGGTTGAACTCCCGAGAGTGTCCTACACTTAGGAGAGAAGCAGCCAAGGGGTTGTTTCCCACCAAGGACGACCCGTCTGCGTGCACGCGGATGAGCCCA
        M  P  R  L  Q  Q  K  W  L  N  S  R  E  C  P  T  L  R  R  E  A  A  K  G  L  F  P  T  K  D  D  P  S  A  C  T  R  M  S  P 
MTV3   ........................................................................................................................
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MTV6   ........................................................................................................................
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                                    50                            60                            70                            80
MTV1   TCAGACAAAGACATACTCATTCTCTGCTGCAAACTTGGCATAGCTCTGCTTTGCCTGGGGCTATTGGGGGAAGTTGCGGTTCGTGCTCGCAGGGCTCTCACCCTTGACTCTTTT---AAT
        S  D  K  D  I  L  I  L  C  C  K  L  G  I  A  L  L  C  L  G  L  L  G  E  V  A  V  R  A  R  R  A  L  T  L  D  S  F  -  N 
MTV3   ..................................................................................................................---...
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MTV6   ...........................................................................................................T......---...
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MTV13  ..............G............................................................................................T......---...
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                                    90                           100                           110                           120
MTV1   AACTCTTCTGTGCAAGATTACAATCTAAACGATTCGGAGAACTCGACCTTCCTCCTGGGGCAAGGACCACAGCCAACTTCCTCTTACAAGCCACACCGACTTTGTCCTTCAGAAATAGAA
        N  S  S  V  Q  D  Y  N  L  N  D  S  E  N  S  T  F  L  L  G  Q  G  P  Q  P  T  S  S  Y  K  P  H  R  L  C  P  S  E  I  E 
MTV3   .G............................A....................................................................T....................
        S  .  .  .  .  .  .  .  .  .  N  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  F  .  .  .  .  .  . 
MTV6   ........C...............................................................................................................
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MTV13  ........................................................................................................................
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                                   130                           140                           150                           160
MTV1   ATAAGAATGCTTGCTAAAAACTATATTTTTACCAATGAGACCAATCCAATAGGTCGATTATTAATCATGATGTTAAGAAATGAATCTTTGTCTTTTAGCACTATATTTACTCAAATTCAA
        I  R  M  L  A  K  N  Y  I  F  T  N  E  T  N  P  I  G  R  L  L  I  M  M  L  R  N  E  S  L  S  F  S  T  I  F  T  Q  I  Q 
MTV3   ....................T...............A..............................CT.................A..AC.......T.....T...............
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MTV6   ....................T...................................................................................................
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MTV13  ....................T...................................................................................................
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                                   170                           180                           190                           200
MTV1   AGGTTAGAAATGGGAATAGAAAATAGAAAGAGACGCTCAACCTCAGTTGAAGAACAGGTGCAAGGACTAAGGGCCTCAGGCCTAGAAGTAAAAAGGGGAAAGAGGAGTGCGCTTGTCAAA
        R  L  E  M  G  I  E  N  R  K  R  R  S  T  S  V  E  E  Q  V  Q  G  L  R  A  S  G  L  E  V  K  R  G  K  R  S  A  L  V  K 
MTV3   ...........................................................A........GTT....A............................................
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MTV6   ........................................................................................................................
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MTV13  ........................................................................................................................
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                                   210                           220                           230                           240
MTV1   ATAGGAGACAGGTGGTGGCAACCAGGGACTTATAGGGGACCTTACATTTACAGACCAACAGACGCCCCGTTACCATATACAGGAAGATATGATTTAAATTTTGATAGGTGGGTCACAGTC
        I  G  D  R  W  W  Q  P  G  T  Y  R  G  P  Y  I  Y  R  P  T  D  A  P  L  P  Y  T  G  R  Y  D  L  N  F  D  R  W  V  T  V 
MTV3   ...........A...................................C..............T.........................................................
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MTV6   ...............................................C.....................C..................................................
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MTV13  ...............................................C.....................C..................................................
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                                   250                           260                           270                           280
MTV1   AACGGCTATAAAGTGTTATACAGATCCCTCCCCTTTCGTGAAAGGCTCGCCAGAGCTAGACCTCCTTGGTGTGTGTTGTCTCAAGAAGAAAAAGACGACATGAAACAACAGGTACATGAT
        N  G  Y  K  V  L  Y  R  S  L  P  F  R  E  R  L  A  R  A  R  P  P  W  C  V  L  S  Q  E  E  K  D  D  M  K  Q  Q  V  H  D 
MTV3   ............................................A................................AA....G....................................
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MTV6   ........................................................................................................................
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MTV13  ........................................................................................................................
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                                   290                           300                           310
MTV1   TATATTTATCTAGGAACAGGAATGATA---CATTGG---AAAGTATTTTATAACAGTAGAGAGGAGGCCAAAAGACATATAATAGAACATATTAAGGCTTTGCCCTTAGCTTTCTAA
        Y  I  Y  L  G  T  G  M  I  -  H  W  -  K  V  F  Y  N  S  R  E  E  A  K  R  H  I  I  E  H  I  K  A  L  P  L  A  F  * 
MTV3   ...........G..G............---......---...........................................................A.........A........
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MTV6   ...........G..G............---......---...........................................................A..................
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MTV13  ...........................---......---...........................................................A..................
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Figure 3. Sequences of Vβ3-specific MTV viral superantigens. Dashes designate spaces to allow alignment with the sequences of the other MTV vSAGs as shown in Fig. 4. These sequence data have been included in the EMBL Data Libraries under accession numbers X63024 (MTV1), X63025 (MTV3), X63026 (MTV6), and X63027 (MTV13).

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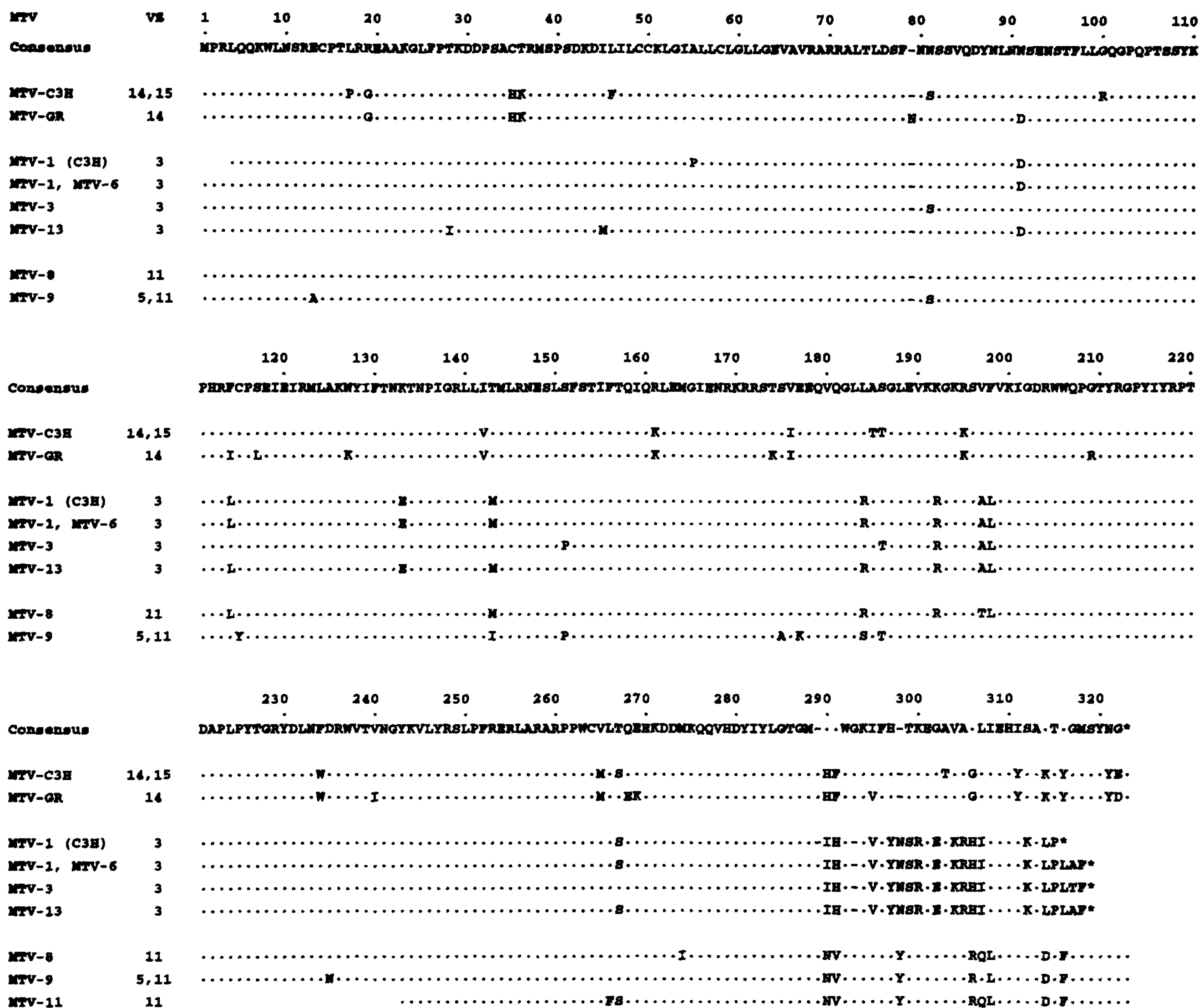

Figure 4. Comparison of amino acid sequences for MTV viral superantigens. The consensus sequence was derived from the published MTV vSAG sequences (36, 38–41).

The finding that all the MTV vSAGs that stimulate Vβ3$^+$ cells have similar sequences, which differ significantly from the other MTV vSAG sequences at the 3′ end, strengthens the hypothesis that the 3′ end of the MTV ORF encodes the Vβ-binding portion of the vSAGs (Fig. 4). This hypothesis is currently being further tested by analyzing T cell responses to chimeric vSAGs.

B cell transfectants expressing the *Mtv*-1 and *Mtv*-3 vSAGs were generated to test whether the products of these genes stimulate Vβ3-bearing T cells. CH12.1, a B cell lymphoma derived from B10.A (28), was used as the recipient cell line. Since B10 congenic mice have high levels of Vβ3 expression (4, 34), we inferred that this B cell would not carry any Vβ3-reactive MTV integrants that might confound the results. Transfectants expressing *Mtv*-1 vSAG or *Mtv*-3 vSAG stimulated Vβ3$^+$ T cell hybrids, K25-49.16 (Table 2) and K25-59.6, while transfectants expressing the hybrid vSAG C3H construct (pUVH) alone did not stimulate these T cells (data not shown). Thus, in conclusion, these experiments confirm that the vSAGs of these endogenous MTV integrants are superantigens, as has been previously demonstrated for the infectious MTVs.

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Table 2. *Stimulation of $V\beta 3^+$ T Cell Hybrids by Transfectants Expressing Mtv-1 ORF or Mtv-3 ORF*

CH12.1 transfectants	IL-2 production by T cell hybrids	
	K25-49.16 (Vβ3)	KOX7-6.6 (Vβ7)
	U/ml	
CMTV1-25	80	–*
CMTV1-35	160	–
CMTV1-40	320	–
CMTV1-43	160	–
CMTV3-4	640	–
CMTV3-8	320	–
CMTV3-27	320	–
CMTV3-4.4‡	160	–
CMTV3-4.5‡	640	–
CMTV3-4.7‡	640	–

* ≤10 U of IL-2/ml.
‡ These transfectants are clones of CMTV3-4.

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References

1. Kappler, J., T. Wade, J. White, E. Kushnir, M. Blackman, J. Bill, R. Roehm, and P. Marrack. 1987. A T cell receptor Vβ segment that imparts reactivity to a class II major histocompatibility complex product. *Cell.* 49:263.
2. Kappler, J.W., U. Staerz, J. White, and P.C. Marrack. 1988. Self-tolerance eliminates T cells specific for Mls-modified products of the major histocompatibility complex. *Nature (Lond.).* 332:35.
3. MacDonald, H.R., R. Schneider, R.K. Lees, R.C. Howe, H. Acha-Orbea, H. Festenstein, R.M. Zinkernagel, and H. Hengartner. 1988. T-cell receptor Vβ use predicts reactivity and tolerance to Mls^a-encoded antigens. *Nature (Lond.).* 332:40.
4. Pullen, A.M., P. Marrack, and J.W. Kappler. 1988. The T cell repertoire is heavily influenced by tolerance to polymorphic self antigens. *Nature (Lond.).* 335:796.
5. Happ, M.P., D. Woodland, and E. Palmer. 1989. A third T cell receptor Vβ gene encodes reactivity to Mls-1^a gene products. *Proc. Natl. Acad. Sci. USA.* 86:6293.
6. Bill, J., O. Kanagawa, D. Woodland, and E. Palmer. 1989. The MHC molecule I-E is necessary but not sufficient for the clonal deletion of Vβ11-bearing cells. *J. Exp. Med.* 169:1405.
7. Okada, C.Y., and I.L. Weissman. 1989. Relative Vβ transcript levels in thymus and peripheral lymphoid tissues from various mouse strains. Inverse correlation of IE and Mls expression with relative abundance of several Vβ transcripts in peripheral lymphoid tissues. *J. Exp. Med.* 169:1703.
8. Tomonari, K., and E. Lovering. 1988. T-cell receptor-specific monoclonal antibody against a Vβ11-positive mouse T cell clone. *Immunogenetics.* 28:445.
9. White, J., A. Herman, A.M. Pullen, R. Kubo, J. Kappler, and P. Marrack. 1989. The Vβ-specific superantigen Staphylococcal enterotoxin B: stimulation of mature T cells and clonal

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deletion in neonatal. *Cell.* 56:27.
10. Kappler, J., N. Roehm, and P. Marrack. 1987. T cell tolerance by clonal elimination in the thymus mice. *Cell.* 49:273.
11. Woodland, D., M.P. Happ, J. Bill, and E. Palmer. 1989. Requirement for co-tolerogenic gene products in the clonal deletion of I-E reactive T cells. *Science (Wash. DC).* 247:964.
12. Woodland, D.L., M.P. Happ, K.A. Gollob, and E. Palmer. 1991. An endogenous retrovirus mediating deletion of $\alpha\beta$ T cells? *Nature (Lond.).* 349:529.
13. Festenstein, H., C. Bishop, and B. Taylor. 1977. Location of Mls locus on mouse chromosome 1. *Immunogenetics.* 5:357.
14. Pullen, A.M., J.W. Kappler, and P. Marrack. 1989. Tolerance to self antigens shapes the T-cell repertoire. *Immunol. Rev.* 107:125.
15. Frankel, W.N., C. Rudy, J.M. Coffin, and B.T. Huber. 1991. Linkage of Mls genes to endogenous mouse mammary tumour viruses of inbred mice. *Nature (Lond.).* 349:526.
16. Dyson, P.J., A.M. Knight, S. Fairchild, E. Simpson, and K. Tomonari. 1991. Genes encoding ligands for deletion of Vβ11 T cells cosegregate with mammary tumour virus genomes. *Nature (Lond.).* 349:531.
17. Marrack, P., E. Kushnir, and J.W. Kappler. 1991. A maternally inherited superantigen encoded by a mammary tumour virus. *Nature (Lond.).* 349:524.
18. Choi, Y., J.W. Kappler, and P. Marrack. 1991. A superantigen encoded in the open reading frame of the 3' long terminal repeat of mouse mammary tumour virus. *Nature (Lond.).* 350:203.
19. Acha-Orbea, H., A.N. Shakhov, L. Scarpellino, E. Kolb, V. Müller, A. Vessaz-Shaw, R. Fuchs, K. Blöchlinger, P. Rollini, J. Billotte, M. Sarafidou, H.R. MacDonald, and H. Diggelmann. 1991. Clonal deletion of Vβ14-bearing T cells in mice transgenic for mammary tumour virus. *Nature (Lond.).* 350:207.
20. Kanagawa, O., E. Palmer, and J. Bill. 1989. The T cell receptor Vβ6 domain imparts reactivity to the Mls-1^a antigen. *Cell. Immunol.* 119:412.
21. Dialynas, D., Z. Quan, K. Wall, A. Pierres, J. Quintans, M. Loken, M. Pierres, and F. Fitch. 1983. Characterization of the murine T cell surface molecule, designated L3T4, identified by monoclonal antibody GK-1.5: similarity of L3T4 to the human Leu 3/T4 molecule and the possible involvement of L3T4 in Class II MHC antigen reactivity. *J. Immunol.* 131:2445.
22. Ledbetter, J., and L. Herzenberg. 1979. Xenogeneic monoclonal antibodies to mouse differentiation antigens. *Immunol. Rev.* 47:63.
23. Maniatis, T., E.F. Fritsch, and J. Sambrook. 1989. Molecular Cloning: A Laboratory Manual. Cold Spring Harbor Laboratory, Cold Spring Harbor, NY.
24. Feinberg, A.P., and B. Vogelstein. 1983. A technique for radiolabeling DNA restriction endonuclease fragments to high specific activity. *Anal. Biochem.* 132:6.
25. Sanger, F., S. Nicklen, and A. Coulson. 1977. DNA sequencing with chain-terminating inhibitors. *Proc. Natl. Acad. Sci. USA.* 74:5463.
26. Pullen, A., T. Wade, P. Marrack, and J. Kappler. 1990. Identification of the region of T cell receptor β chain that interacts with the self-superantigen Mls-1^a. *Cell.* 61:1365.
27. Shackleford, G.M., and H.E. Varmus. 1988. Construction of a clonable, infectious, and tumorigenic mouse mammary tumor virus provirus and a derivative genetic vector. *Proc. Natl. Acad. Sci. USA.* 85:9655.
28. Arnold, L., N. LoCascio, P. Lutz, A. Pennell, D. Klapper, and G. Haughton. 1983. Antigen-induced lymphomagenesis: identification of a murine B cell lymphoma with known antigen specificity. *J. Immunol.* 131:2064.
29. Kappler, J., B. Skidmore, J. White, and P. Marrack. 1981. Antigen-inducible, H-2-restricted, interleukin 2 producing T cell hybridomas. Lack of independent antigen and H-2 recognition. *J. Exp. Med.* 153:1198.
30. Pullen, A.M., P. Marrack, and J. Kappler. 1989. Evidence that Mls-2 antigens which delete V$\beta 3^+$ T cells are controlled by multiple genes. *J. Immunol.* 142:3033.
31. Abe, R., and R.J. Hodes. 1989. T-cell recognition of minor lymphocytes stimulating (Mls) gene products. *Annu. Rev. Immunol.* 7:683.
32. Abe, R., M. Foo-Phillips, and R.J. Hodes. 1989. Analysis of Mls^c genetics. A novel instance of genetic redundancy. *J. Exp. Med.* 170:1059.
33. Marrack, P., M. Blackman, E. Kushnir, and J. Kappler. 1990. The toxicity of staphylococcal enterotoxin B is mediated by T cells. *J. Exp. Med.* 171:455.
34. Abe, R., M. Foo-Phillips, and R.J. Hodes. 1991. Genetic analysis of the Mls system. Formal Mls typing of the commonly used inbred strains. *Immunogenetics.* 33:62.
35. Fairchild, S., A.M. Knight, P.J. Dyson, and K. Tomonari. 1991. Co-segregation of a gene encoding a deletion ligand for Tcrb-V3$^+$ T cells with Mtv-3. *Immunogenetics.* 34:227.
36. Crouse, C., and R.J. Pauley. 1989. Molecular cloning and sequencing of the MTV-1 LTR: evidence for LTR sequence alteration. *Virus. Res.* 12:123.
37. Lee, B.E., and E.M. Eicher. 1990. Segregation patterns of endogenous mouse mammary tumor viruses in five recombinant inbred strain sets. *J. Virol.* 64:4568.
38. Majors, J.V., and H. Varmus. 1983. Nucleotide sequencing of an apparent proviral copy of env mRNA defines determinants of expression of the mouse mammary tumor virus env gene. *J. Virol.* 47:495.
39. Donehower, L.A., A.L. Huang, and G.L. Hager. 1981. Regulatory and coding potential of the mouse mammary tumor virus long terminal redundancy. *J. Virol.* 37:226.
40. Donehower, L.A., B. Fleurdelys, and G.L. Hager. 1983. Further evidence for the protein coding potential of the mouse mammary virus long terminal repeat: nucleotide sequence of an endogenous proviral long terminal repeat. *J. Virol.* 45:491.
41. King, L.B., F.E. Lund, D.A. White, S. Sharma, and R.B. Corley. 1990. Molecular events in B lymphocyte differentiation: inducible expression of the endogenous mouse mammary tumor proviral gene, Mtv-9. *J. Immunol.* 144:3218.

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