Proteolytic Processing Is Required for Viral Superantigen Activity

By Chae Gyu Park, Mi-Young Jung, Yongwon Choi, and Gary M. Winslow

From the Howard Hughes Medical Institute, The Rockefeller University, New York 10021; and the Howard Hughes Medical Institute, Division of Basic Immunology, Department of Medicine, National Jewish Center for Immunology and Respiratory Medicine, Denver, Colorado 80206

Summary

The mouse mammary tumor virus-7 superantigen (vSAG7) is proteolytically processed in B cells at as many as three positions. Proteolytic processing appears to be important for superantigen activity because a processed form of vSAG7 was predominant among those forms that were found to bind to major histocompatibility complex class II molecules. To determine the functional significance of proteolytic processing, a mutation was introduced in vSAG7 at one of the sites where proteolytic cleavage is thought to take place in B cells. Elimination of the putative processing site at position 171 abrogated detectable vSAG7 surface expression in B cells, indicating that proteolytic processing is required for vSAG7 function. Coexpression in insect cells of vSAG7 and furin, a proprotein-processing enzyme, also demonstrated that furin could process vSAG7 at position 171.

Superantigens bind to MHC class II molecules and stimulate T cells that bear specific Vβs as part of their TCR (1, 2). They are encoded by bacteria and by mouse mammary tumor viruses (MMTVs). The soluble bacterial superantigens have been well characterized at the biochemical and cellular levels, but the biochemical nature of the MMTV superantigens (vSAGs) has been obscure. Biochemical studies of the superantigen encoded by MMTV7 (vSAG7) have indicated that vSAG7 is detected on the cell surface in a proteolytically processed form (3). Proteolytic processing is thought to occur in the Golgi region or in a post-Golgi compartment and yields a product(s) that is (are) cleaved at as many as three positions (4). At least one processed form of the protein has been shown to bind to MHC class II molecules (4). It has not been determined, however, if processing is required for normal vSAG7 function, and the exact positions in the protein where the proteolytic processing occurs are unknown.

vSAG7 is among a number of viral glycoproteins and cellular protein precursors that undergo proteolytic processing. Proteolytic cleavage of the precursor proteins commonly occurs at sites characterized by paired basic residues and is thought to result from the action of any of a family of mammalian subtilisin-like serine proteases (also known as proprotein convertases [PCs]) (5, 6). In several cases, proteolytic processing has been shown to be required for protein activity (7–10).

Analysis of the vSAG7 amino acid sequence suggested the presence of three possible basic endoprotease recognition sites at residues 68–71 (RARR in single-letter amino acid code), 168–171 (RKRR), and 190–194 (KEGKR). The approximate molecular weights of the vSAG7 proteolytic products that have been detected using SDS-PAGE are consistent with those predicted to be generated if cleavage occurred at or near these putative processing sites (4). Although a vSAG7 product, probably processed at residues 168–171, predominated among the forms found to be associated with class II I-Aκ (4), it has not been determined if proteolytic processing of vSAG7 is required for presentation to T cells.

To determine the importance of residues 168–171 for proteolytic cleavage and vSAG7 function, amino acid substitutions were introduced at this position in vSAG7 using site-directed mutagenesis, and the effects of the substitutions on vSAG7 function were examined at the cellular and biochemical levels. In this study, we show that proteolytic cleavage was required for vSAG7 surface expression in B cells and presentation to T cells. In addition, the furin endoprotease, which recognizes the amino acid motif RXK/RR, is shown to be a candidate vSAG7-processing endoprotease.

Materials and Methods

Mutagenesis and Plasmids. To generate each mutant sag7 gene, the sag7 gene was amplified by PCR with mutagenic primers, as shown in Fig. 1 B. For the sag7m171 mutation, two different PCR products of the sag7 gene were amplified in separate reactions. One reaction used the 5′ m171 primer (5′-GAAAAATGGAGAGGATTCTCAACCGAG-3′) and primer B (5′-GGGGATCCCTAAAGGGATCGAAGCCGA-3′), and the other reaction used the 3′ m171 primer (5′-TGGCGTGGAGAATCCTCCTCTCATTTC-3′) and primer A (5′-GGGAATTCTCAGAGATGCGCCTGC-3′).

1899 J. Exp. Med. © The Rockefeller University Press • 0022-1007/95/05/1899/06 $2.00
Volume 181 May 1995 1899-1904
3'). The two products obtained in the first PCR were joined together in the second round of the PCR, as described previously (11), with primers A and B, to generate the complete sag7*mut gene (Fig. 1 B). The sag7*mut mutation was generated in a similar manner as sag7*mut, except that different mutagenic primers were used: the 5' m194 primer (5'-AGAAGGAGAATTCAGTGTG-Y) and the 3' m194 primer (5'-AGAAGGAGAATTCAGTGTG-Y) and primer B, described above, using the wild-type or mutant sag7 genes as templates. The soluble forms lack the cytoplasmic domain and transmembrane portion of vSAG7. The soluble forms were created by fusion in frame to the human TCR, V813 signal peptide (MAIGLICLCAALSLLWAGPVNA3VTQ; 1 = signal peptide cleavage site; 12). After verifying the sequences of each PCR product, the genes encoding the soluble forms of vSAG7 were cloned into a baculovirus expression vector pBACp10pH (derived from pACUW51; PharMingen, San Diego, CA) (13) to generate the plasmids pBseg7, pBseg7*mut, and pBseg7*mut. The human furin (also known as PACE) cDNA was isolated from pMT3, kindly provided by Dr. A. Rehemtulla (Howard Hughes Medical Institute, University of Michigan Medical Center, Ann Arbor, MI), and ligated into pBACp10pH to create the plasmid pBAC-furin (14).

Cell Culture, Transfections, and Flow Cytometric Analysis. The culture of B cell lymphoma CH12.1 and the T cell hybridomas have been described previously (3, 11, 15). Spodoptera frugiperda (SF9) cells were cultured in Grace's media (GIBCO BRL, Gaithersburg, MD) supplemented with 10% FCS, 100 µg/ml penicillin G, 200 µg/ml streptomycin, and 0.25 µg/ml amphotericin B. To generate B cell lines expressing vSAGs, the wild-type and sag7*mut genes were inserted into pH•APr-l-neo and transfected by electroporation into the B cell lymphoma CH12.1, as described previously (11). The transfectants were also examined for their ability to stimulate the T cell hybridomas by measuring lymphokine production, as described previously (3). Flow cytometry was performed on a FACScan® (Becton Dickinson & Co., Mountain View, CA) flow cytometer, as described previously (3, 4).

Production of vSAG7 and Furin in Insect Cells. Recombinant baculoviruses were produced by transfecting the transfer plasmids pBseg7, pBseg7*mut, and pBseg7*mut, and pBAC-furin with rescue viral DNAs into SF9 cells using a transfection kit (BaculoGold™; PharMingen), following conditions as described previously (3). Purification of vSAG7 bound to class II I-A* was performed as described previously (4).

Results and Discussion

Proteolytic Processing Is Required for vSAG7 Presentation. The three putative processing sites in vSAG7 have been defined previously as the transmembrane (residues 68–71; RARR), proximal (168–171; RKRR), and distal (190–194; KEGKR) cleavage sites (5, 6) (Fig. 1 A). In particular, it has been suggested that proteolytic cleavage at the proximal site may be required for the binding of vSAG7 to MHC class II molecules (4). To directly test if proximal cleavage site–dependent processing was required for vSAG7 presentation to T cells, amino acid substitutions were made at the proximal site by site-directed mutagenesis. The substitutions introduced acidic and hydrophobic residues in place of the tetrabasic sequence (RKRR, KR), and the sites of N-linked glycosylation (branched). A strategy used for construction of baculovirus–vSAG7 expression vectors. A portion of the amino acid sequence of the signal peptide and the position of the signal peptide cleavage site are shown.
vSAG7 was analyzed by flow cytometry using the monoclonal antibody VS7, which recognizes the COOH terminus of vSAG7 (3). CH12.1/S7, the cell line transfected with the wild type sag7 gene, showed a significant level of vSAG7 surface expression, as previously reported (11). In contrast, no surface expression of class II MHC proteins in the transfectants were not significantly different (data not shown).

T cell recognition is more sensitive than flow cytometry for assay of vSAG7 expression on B cells, so the transfectants were also tested for their ability to stimulate appropriate T cell hybridomas. CH12.1/S7 stimulated T cell hybridomas, which expressed the vSAG7-responsive Vβ elements Vβ6 and Vβ8.1, but these same hybridomas were not stimulated by CH12.1/S7m171 (data not shown). The data suggest that the mutant vSAG7 was not transported to the surface, or was nonfunctional. The absence of detectable surface expression of vSAG7m171 in these cells was probably not caused by a failure in protein production because a significant amount of intracellular protein was detected (Fig. 3). Therefore, proteolytic processing appeared to be critical for vSAG7 presentation to T cells and/or for proper surface expression.

To determine if the vSAG7m171 underwent any proteolytic processing, the protein was partially purified and analyzed biochemically. In experiments using CH12.1/S7, VS7 detected several forms of vSAG7, including a precursor protein (gpPr45m), and two COOH-terminal proteolytic cleavage products, previously defined as p18 and p16 (Fig. 3). It was suggested that p18 and p16 originated as a result of proteolytic processing at the proximal and distal vSAG7 cleavage sites, respectively. In affinity-purified preparations of vSAG7m171, gpPr45m was detected, but only a single COOH-terminal cleavage product was apparent (Fig. 3, lane 2). Comparison of the vSAG7m171 with wild-type vSAG7 revealed that the cleavage product detected in preparations of CH12.1/S7m171 protein corresponded to the cleavage product p16, indicating that the m171 substitution eliminated the production of p18 in B cells (Fig. 3, lanes 1 and 2). Therefore, p18 in vSAG7 originated most likely after proteolytic processing at the proximal cleavage site, as has been previously suggested (4).

It has been demonstrated previously that p18, but not p16, binds to the class II molecule I-Ak (4). To further support the conclusion that the vSAG7m171 proteolytic cleavage product was indeed p16, the migration of vSAG7m171 was compared with vSAG7 products that were found to bind to I-Ak (Fig. 3 b). The data in Fig. 3 b demonstrate that the vSAG7m171 cleavage product does not comigrate with the vSAG7 cleavage product, p18, that was found to bind to I-Ak.

The Transmembrane and Proximal Proteolytic Processing Sites Are Substrates for the Endoprotease Furin. The basic amino acid proteolytic cleavage sites that have been described in
vSAG7 are potential substrates for PCs. One PC, furin, has been detected in most mammalian cell types, including thymus and spleen (19, 20), unlike other PCs, which are expressed primarily in neuroendocrine tissues (21, 22). Therefore, experiments were performed to determine if furin could act as a vSAG7-processing endoprotease.

A soluble form of vSAG7 (BvSAG7) was engineered by truncation of the cytoplasmic and transmembrane regions and by introduction of a signal peptide to facilitate secretion. BvSAG7 was expressed in Sf9 cells after infection with recombinant baculoviruses containing the Bsag7 gene (Fig. 1 C). BvSAG7 was detected in the culture medium by Western analysis using the VS7 antibody. BvSAG7 was secreted from Sf9 cells in three forms: an N-glycosylated major product of 36 kD (gp36), a minor N-glycosylated product of 33 kD (gp33), and a nonglycosylated proteolytic product, p18 (Fig. 4, lanes 1 and 5). The N-glycosylation status of the products were determined using N-glycanase (data not shown).

Similar results were obtained in parallel experiments using recombinant baculoviruses that expressed a form of BvSAG7 that contained a peptide epitope at the NH2 terminus of the secreted protein. The peptide allowed BvSAG7 to be recognized by the mAb 12CA5 (23). Among the three secreted protein products recognized with VS7 antibody, only the major protein product, gp36, was also recognized by 12CA5 antibody (Park, C. G., M. Y. Jung, and Y. Choi, unpublished data). These data indicated that the major product (gp36) was the full-length BvSAG7 protein and the other proteins were proteolytic processing products.

The p18 secreted by the Sf9 cells was similar in size to the COOH-terminal cleavage product of vSAG7 detected in B cells, and gp33 was hypothesized to originate from proteolytic cleavage at the RARR sequence found at residues 15–18 of the recombinant protein, BvSAG7 (Fig. 1 C). The data suggested that Sf9 cells contain an endogenous furinlike activity, as has been suggested (24), and that BvSAG7 protein can undergo limited proteolytic processing in insect cells.

BvSAG7 was also treated with membrane fractions prepared from Sf9 cells expressing the human furin gene. Under these conditions, the amount of the proteolytic cleavage products p18 and gp33 increased to two- to threefold relative to the full-length gp36 protein (Fig. 4). Similar results were obtained when BvSAG7 was coexpressed with furin in Sf9 cells (Fig. 4, lanes 5–8). Therefore, BvSAG7 was a substrate for furin. The enhanced production of gp33 upon treatment with the furin-containing membrane fractions also suggested that the putative transmembrane cleavage site (RARR) was a substrate for the furin endoprotease.

To identify the COOH-terminal cleavage site recognized by human furin, soluble forms of vSAG7m171 (BvSAG7m171) and a second mutant protein, BvSAG7m194, were also expressed in Sf9 cells. BvSAG7m194 contains substitutions at residues 193–194 (KR changed to EF) that were predicted to eliminate the distal putative proteolytic processing site. Because the distal processing site did not appear to be recognized by furin in insect cells, it was not possible to examine the effect of the amino acid substitutions on processing at this site. However, BvSAG7m194 migrated in a manner similar to BvSAG7, and coexpression with furin greatly enhanced production of the COOH-terminal cleavage product p18 (Fig. 4, lanes 7 and 8). In contrast, p18 was not generated as a proteolytic cleavage product of BvSAG7m171, either in the presence or absence of furin (Fig. 4, lanes 3 and 4 and lanes 9 and 10).

These data suggested that in Sf9 cells, p18 was generated by proteolytic processing at the proximal cleavage site (RKRR) of vSAG7, as in B cells, and this site was a substrate for furin. These results are consistent with the earlier interpretation that vSAG7 processing occurs in the Golgi region or a post-Golgi compartment (4), where furin has been shown to be localized (25). Furthermore, the results also indicate that the putative distal processing site was not a substrate for furin. This suggests that a processing enzyme other than furin may generate the COOH-terminal cleavage product p16, that the distal site is not accessible to furin in BvSAG7, or that the specificity of furin may differ between insect and B cells. The analyses have not localized the precise site of the distal cleavage event used to generate p16.

The data presented here show that proteolytic processing is required for T cell stimulation and/or surface expression of vSAG7 in B cells. Because full-length vSAG7 has not been unambiguously detected on the cell surface of an APC, it is unknown if vSAG7 will activate T cells in the absence of proteolytic processing. Nevertheless, the data presented here demonstrate that proteolytic processing is a requisite event for viral superantigen presentation by APC.

Earlier work suggested that proteolytic processing at the proximal endoprotease site may enhance binding of vSAG7 to class II MHC (4). vSAG7m171 was not proteolytically
References

1. Scherer, M.T., L. Ignatowicz, G. Winslow, J.W. Kappler, and P. Marrack. 1993. Superantigens: bacterial and viral proteins that manipulate the immune system. *Annu. Rev. Cell Biol.* 9:101-128.

2. Kotzin, B.L., D.Y.M. Yeung, J. Kappler, and P. Marrack. 1993. Superantigens and their potential role in human disease. *Adv. Immunol.* 54:99-166.

3. Winslow, G.M., M.T. Scherer, J.W. Kappler, and P. Marrack. 1992. Detection and biochemical characterization of the mouse mammary tumor virus 7 superantigen (Mls-1). *Cell.* 71:719-730.

4. Winslow, G.M., P. Marrack, and J.W. Kappler. 1994. Processing and major histocompatibility complex binding of the MTV7 superantigen. *Immunity.* 1:23-33.

5. Barr, P.J. 1991. Mammalian subtilisins: the long-sought dibasic processing endoproteases. *Cell.* 66:1-3.

6. Steiner, D.F., S.P. Smeekens, S. Ohagi, and S.J. Chan. 1992. The new enzymeology of precursor endoproteases. *J. Biol. Chem.* 267:23435-23438.

7. McCune, J.M., L.B. Rabin, M.B. Feinberg, M. Lieberman, J.C. Kosek, G.R. Reyes, and I.L. Weissman. 1988. Endoproteolytic cleavage of gp160 is required for the activation of human immunodeficiency virus. *Cell.* 53:55-67.

8. Hallenberger, S., V. Bosch, H. Angliker, E. Shaw, H.-D. Klenk, and W. Garten. 1992. Inhibition of furin-mediated cleavage activation of HIV-1 glycoprotein gp160. *Nature (Lond.)* 360:358-361.

9. Dong, J., J.W. Dubay, L.G. Perez, and E. Hunter. 1992. Mutations within the proteolytic cleavage site of the Rous sarcoma virus glycoprotein define a requirement for dibasic residues for intracellular cleavage. *J. Virol.* 66:865-874.

10. Klenk, H.-D., and R. Rott. 1988. The molecular biology of influenza virus pathogenicity. *Adv. Virus Res.* 34:247-281.

11. Yazdanbakhsh, K., C.G. Park, G.M. Winslow, and Y. Choi. 1993. Direct evidence for the role of carboxyl terminus of mouse mammary tumor virus superantigen in determining TCR Vβ specificity. *J. Exp. Med.* 178:737-741.

12. Choi, Y., A. Herman, D. DiGusto, T. Wade, P. Marrack, and J. Kappler. 1990. Residues of the variable region of the T-cell receptor β-chain that interact with the *S. aureus* toxin superantigens. *Nature (Lond.)* 346:471-473.

13. Kozono, H., J. White, J. Clements, P. Marrack, and J. Kappler. 1994. Functional soluble MHC class II proteins with covalently bound single peptide. *Nature (Lond.)* 369:151-154.

14. Rehemtulla, A., and R.J. Kaufman. 1990. Preferred sequence requirements for cleavage of Pro-vonWillebrand factor by propeptide-processing enzymes. *Blood.* 79:2349-2355.

15. Arnold, L.W., N.J. LoCascio, P. Lutz, C.A. Pennell, D. Klapper, and G. Haughton. 1983. Antigen-induced lymphogenesis: identification of a murine B cell lymphoma with known antigen specificity. *J. Immunol.* 131:2064-2068.

16. Vidiciraie, G., J.-B. Denault, and R. Lecud. 1993. Characterization of a secreted form of human furin endoprotease. *Biochem. Biophys. Res. Commun.* 195:1011-1018.

17. Leduc, R., S.S. Molloy, B.A. Thorne, and G. Thomas. 1992. Activation of human furin precursor processing endoprotease occurs by an intramolecular autoproteolytic cleavage. *J. Biol. Chem.* 267:14304-14308.

18. Gunning, P., J. Leavitt, G. Muscat, S.-Y. Ng, and L. Kedes. 1987. A human ß-actin expression vector system directs high-level accumulation of antisense transcripts. *Proc. Natl. Acad. Sci. USA.* 84:4831-4835.

19. Hatsuzawa, K., M. Hosaka, T. Nakagawa, M. Nagase, A. Shoda, K. Murakami, and K. Nakayama. 1990. Structure and expression of mouse furin, a yeast Kex2-related protease. *J. Biol. Chem.* 265:22075-22078.

20. Schalken, J.A., A.J.M. Roobroeck, R.P.C.A. Oomen, S.S. Wagenaar, E.M.J. Debruynr, H.P.J. Bloemers, and W.J.M. Van de Ven. 1987. *fur* gene expression as a discriminating marker for small cell and nonsmall cell lung carcinomas. *J. Clin. Invest.* 80:1545-1549.

21. Seidah, N.G., M. Marcinkiewicz, S. Benjannet, L. Gaspar, G. Beaubien, M.G. Mattei, C. Lazure, M. Mbiay, and M. Chretien. 1991. Cloning and primary sequence of a mouse candi...
date prohormone convertase PC1 homologous to PC2, furin, and kex2: distinct chromosomal localization and messenger RNA distribution in brain and pituitary compared to PC2. Mol. Endocrinol. 5:111–122.

22. Smeekens, S.P., A.S. Avruch, J. LaMendola, S.J. Chan, and D.F. Steiner. 1991. Identification of a cDNA encoding a second putative prohormone convertase related to PC2 in AtT20 cells and islets of Langerhans. Proc. Natl. Acad. Sci. USA. 88: 340–344.

23. Kolodziej, P., and R.A. Young. 1991. Epitope tagging and protein surveillance. Methods Enzymol. 194:508–519.

24. Wells, D.E., and R.W. Compans. 1990. Expression and characterization of a functional human immunodeficiency virus envelope glycoprotein in insect cells. Virology. 176:575–586.

25. Molloy, S.S., L. Thomas, J.K. VanSlyke, P.E. Stenberg, and G. Thomas. 1994. Intracellular trafficking and activation of the furin proprotein convertase: localization to the TGN and recycling from the cell surface. J. Biol. Chem. 13:18–33.