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Mannose-Binding Lectin (MBL)-Associated Serine Protease (MASP)-1 Contributes to Activation of the Lectin Complement Pathway

Minoru Takahashi,* Daisuke Iwaki,* Kazuko Kanno,* Yumi Ishida,* Jie Xiong,§ Misao Matsushita,¹ Yuichi Endo,* Shigeto Miura,‡ Naoto Ishii,§ Kazuo Sugamura,‡ and Teizo Fujita²*

The complement system plays an important role in innate immunity. In the lectin complement pathway, mannos-binding lectin (MBL) and ficolins act as recognition molecules, and MBL-associated serine protease (MASP) is a key enzyme. It has been suggested that MASP-2 is responsible for the activation of C4. Other serine proteases (MASP-1 and MASP-3) are also associated with MBL or ficolins; however, their functions are still controversial. In this study, a MASP-1- and MASP-3-deficient mouse model was generated by a gene targeting strategy to investigate the roles of MASP-1 and MASP-3 in the lectin pathway. Serum derived from MASP1/3−/− mice showed significantly lower activity of both C4 and C3 deposition on mannan-agarose, and this low activity was restored by the addition of recombinant MASP-1. MASP-1/3-deficient serum showed a significant delay for activation of MASP-2 compared with normal serum. Reconstitution of recombinant MASP-1 in MASP-1/3-deficient serum was able to promote the activation of MASP-2. From these results, we propose that MASP-1 contributes to the activation of the lectin pathway, probably through the activation of MASP-2. The Journal of Immunology, 2008, 180: 6132–6138.

In the lectin pathway, mannos-binding lectin (MBL)³ or ficolins recognize carbohydrates (such as mannose and N-acetylgalcosamine) on microorganisms (5, 6). Activation of the pathway is triggered by serine proteases that are associated with MBL or ficolins, termed MAMPS (MBL-associated serine proteases) (7). MASPs are similar to C1r and C1s in the classical pathway, and have highly conserved domain structures, including C1r/C1s/Uegf/bone morphogenetic protein 1, epidermal growth factor-like, C1r/C1s/Uegf/bone morphogenetic protein 2, short consensus repeat 1, short consensus repeat 2, and serine protease domains. Three kinds of MASP, MASP-1 (7), MASP-2 (8), MASP-3 (9), and a truncated form of MASP, sMAP (10, 11), are present in MBL and ficolin complexes. Some in vitro evidence has suggested that MASP-2 alone is sufficient to trigger complement activation. First, only MASP-2 has proteolytic activity toward C4 and C2, similar to C1s in the classical pathway, although MASP-1 is able to cleave C2 (8, 12). Second, recombinant MASP-2 is easily activated by itself during purification (13), indicating that autoactivation of MASP-2 might occur in the lectin pathway cascade. However, the role of MASP-1 in the lectin pathway is still controversial; MASP-1 is capable of cleaving C3 directly (9, 14, 15), resulting in activation of the alternative pathway (14). These results suggest that there might be another route, independent of MASP-2, for the activation of the complement system (14). However, it has not been confirmed whether cleavage of C3 by MASP-1 would actually involve activation of the lectin pathway in vivo, as MASP-1 activity is very low (16). The function of MASP-3 is not yet clear. MASP3 mRNA
is transcribed by an alternative splicing/polyadenylation mechanism from the MASP1/3 gene, in which the regions encoding the serine protease domains of MASP-3 and MASP-1 are tandemly located (9).

In mouse, the MBL-MASP complex was first described as a Ra-reactive factor that binds specifically to Ra chemotype strains of *Salmonella* (17). Murine MASP-1 (18) and MASP-2 (19) have already been cloned and characterized. We previously described murine MASP-3 cDNA from the livers of C57BL/6J mice (20). In the present study, we generated MASP-1 and MASP-3 double-deficient mice using a standard gene targeting method. This knock-out mouse showed insufficient abilities to activate C3, C4, and C5 in the serum of two ES clones into C57BL/6J blastocysts. Germline transmissions were achieved in the offspring of both chimeric mice, by backcrossing with a C57BL/6J line. The targeted locus was maintained by breeding of heterozygous mice with wild-type C57BL/6J. Homozygous mice were generated by crossing two independent mice from the same litter. The targeted allele was confirmed in four ES clones. Two independent chimeric mice were generated by microinjection of the targeting vector (21), and the mutated allele (22). In the map of the wild-type gene, the region from the first exon to the third is depicted; the closed boxes show exons. The translation initiation site is located in the first exon. neo and DT-A indicate a neomycin-resistant gene and a diphtheria toxin cassette, respectively. The restrictions sites are as follows: Xb, Xhol; B, BamHI; S, Sall; and Sc, SacI. B, Southern blot analysis of progenies from MASP1/3 wild-type intercrosses. Genomic DNA was digested with BamHI and hybridized with a BamHI-Sall fragment of genomic DNA, including part of the first intron. The location of the probe is indicated with bars under the wild and targeted alleles.

**Materials and Methods**

**Generation of MASP1/3-deficient mice**

Genomic DNAs, including the murine MASP1/3 gene, were isolated from a 129SV phage genomic library (Stratagene). The targeting vector was constructed as illustrated in Fig. 1A and transfected into 11 cells by electroporation. After selection with 200 μg/ml G418 (Invitrogen), embryonic stem (ES) clones were picked up, and their genotypes were analyzed by Southern blotting using a BamHI-Sall fragment of genomic DNA as a probe. The expected homologous recombination was confirmed in four ES clones. Two independent chimeric mice were generated by microinjection of two ES clones into C57BL/6J blastocysts. Germline transmissions were achieved in the offspring of both chimeric mice, by backcrossing with a C57BL/6J line. The targeted locus was maintained by breeding of heterozygous mice with wild-type C57BL/6J. Homozygous mice were generated by mating of heterozygous pairs. The genotypes of mice were determined by PCR using tail genomic DNA as a template. Wild-type-specific alleles were amplified as 539 bp fragments using the primers set M1U: 5′-ACCCCTCTCCCTCAGCAGCTTTTGGATA-3′ and M1L: 5′-GGCTGATGCTGTGTTAGGTAGGATTC-3′; the mutant allele was detected as 639 bp fragment by using M1L with another primer, NeoU: 5′-CATTGCGCTTCTATCGCCTTCTTGAGTGTGTTTGT-3′. Mice in this study were used according to the guidelines for animal experimentation of Fuku-shima Medical University.

**RT-PCR for murine MASP3 and Gapdh**

Murine liver mRNA was purified by using PolyATtract system 1000 (Promega). First strand cDNA was synthesized from 1 μg of messenger RNA using the Ready-To-Go T primed first strand kit (GE Healthcare Bio-Sciences). PCR was conducted using 1 μl of the first strand cDNA as template and the primer sets: 1F (5′-CAGAGCGMAASP-1, M1L: 5′-GCAGACGGCTGTTTGGATA-3′, and 2R (5′-GCGACCTCCGATGATTTCTC-3′) for MASP3, and 5′-GTATGTCTGGAGTGCTCAGAAGAGCAGGTT-3′ for Gapdh.

**Recombinant murine MASP-1**

To assess the enzymatic effect of MASP-1, two kinds of recombinant murine MASP-1 (recombinant native type of MASP-1 (rMASP-1n) and recombinant MASP-1 mutant modified by replacing the arginine429 with lysine (rMASP-1K)) have been expressed and purified in insect cells. Native type of recombinant MASP-1 was defined as rMASP-1n. Mutant type of recombinant MASP-1 was defined as rMASP-1K in which the arginine429 was replaced with lysine. In addition, we used recombinant inactive MASP-1 mutant (rMASP-1i) in which the serine617 was replaced with alanine.

Two recombinants, rMASP-1n and rMASP-1i were generated as follows. The cDNA encoding the entire coding region of the MASP1 gene was amplified by RT-PCR. A sequence encoding 6× His was added at the 3′-end of the cDNA instead of the native stop codon. The cDNA was ligated into pVL1393 vector (BD Biosciences), to generate rMASP-1n. To construct rMASP-1i, the codon for the serine residue at amino acid position 627, essential for the active center of MASP-1, was replaced with an alanine using site-directed mutagenesis based on PCR. Both plasmid constructs were transfected into Sf21 cells with BacPAK6 viral DNA (BsaMidi digest) using Bacfectin reagent (BD Biosciences). After incubation for 3 days at 27°C, recombinant virus was harvested from culture supernatants. Virus plaques were made by infection of virus into an agarose-fixed monolayer of Sf21 cells. Four plaques were picked up from each construct.

These virus stocks were further amplified by infection into Sf21 cells. For expression of recombinant proteins, Sf21 cells were routinely cultured in 500-ml Erlenmeyer flasks containing 200 ml of S90011 serum-free medium (Invitrogen). For large scale preparation, 300 ml of Sf21 cells (0.5×10^6/ml) were infected with recombinant baculovirus by 5–10 multiplicity of infection. To purify recombinant proteins, culture supernatant was concentrated with a concentrator (Millipore) to approximately 1 milligram of recombinant protein. Recombinant proteins were captured on HisTrap columns (GE Healthcare Bio-Sciences) at 0.5 ml/min. Captured proteins were eluted by a gradient (from 0 to 30%) of elution buffer containing 20 mM TrisCl (pH 7.4), 0.5 M NaCl, 5 mM CaCl2, and 10 mM imidazole and recombinant proteins were captured on HisTrap columns (GE Healthcare Bio-Sciences) at 0.5 ml/min. Captured proteins were eluted by a gradient (from 0 to 30%) of elution buffer containing 20 mM TrisCl (pH 7.4), 0.5 M NaCl, 5 mM CaCl2, and 0.5 M imidazole). Fractions including MASP-1 were estimated by Western blotting using anti-MASP-1 Ab and pooled fractions were dialyzed with TBS.

The procedure to make another recombinant, rMASP-1K, was described as below. Murine MASP1 cDNA that includes its full coding region and an artificial histidine-tag at C terminus was subcloned in an expression vector, pBfVS-His (Invitrogen). A codon that encodes the arginine residue at active site P1 cleavage of MASP-1 between H and L chains was replaced with a codon for lysine residue using a QuikChange kit (Stratagene). This vector was transfected in an insect cell line, High-Five by FuGENE HD transfection reagent (Roche Diagnostic Systems). Stable transfectants were selected in Ex-Cell 405 medium (SAFC Biosciences) containing 10 μg/ml blasticidin (Invitrogen). Transfectants were further cultured in a suspension using an Erlenmeyer flask with shaking. To get recombinant MASP-1K, >1.6×10^6 cells/ml transfectants was seeded in 200 ml of fresh Ex-Cell 405 medium containing 1 μg/ml aprotinin and 10 μg/ml blasticidin. Approximately 1 milligram of rMASP-1K could be purified from 200 ml of culture supernatant by binding to 1 ml of TALON resin (Clontech Laboratories). Protein concentration was estimated by BCA protein assay kit (Pierce).

**Expression and purification of recombinant murine MASP-2i**

Recombinant murine MASP-2, in which the serine residue at the active center of the protease domain was replaced with an alanine, was expressed in Drosophila Schneider 2 cells and purified by a nickel column as described (21).
Polyclonal Abs against murine MASP-1 and MASP-2

Two kinds of polypeptide corresponding to the regional sequences of the L chain of MASP-1 (Glu63 to Asn680) and the H chain of MASP-2, including the sMAP region (Thr106 to Leu200), were expressed as recombinant proteins using a pET21a vector (Novagen) in Escherichia coli. The products were purified from a gel after SDS-PAGE by electro-elution (Bio-Rad). Polyclonal Abs were prepared by immunizing rabbits with the purified polypeptides as Ags. These Abs react with the denatured protein in SDS-PAGE. To establish a polyclonal Ab that recognizes native MASP-1, a rabbit was immunized with rMASP-1i.

Detection of MASP-1 in murine sera on mannan-coated plates

Maxi-Sorp plates (Nunc) were coated with 100 µl of 10 µg/ml mannan (M3640; Sigma-Aldrich) in sodium carbonate buffer (pH 9.6) soaked overnight. Blocking was done by adding 1% BSA in TBS/5 mM CaCl2 (TBS/Ca) buffer. After washing with TBS/Ca containing 0.05% Tween 20 (TBS/Ca/tw), serially diluted murine serum in TBS/Ca/tw was added to the wells. After incubation for 30 min at 37°C, the wells were washed four times with TBS/Ca/tw. Each well was incubated with polyclonal anti-mouse MASP-1 for 30 min at room temperature, and then washed four times with TBS/Ca/tw. The wells were further incubated with HRP-conjugated anti-rabbit Ig for 30 min. Enzymatic color development was achieved by 1M H3PO4. Color was detected by the absorbance at 450 nm.

Western blotting of MBL-MASP complexes eluted from mannan-agarose

Mouse serum was diluted with TBS/Ca buffer. The diluted serum was incubated with 20 µl of mannan-agarose (Sigma-Aldrich). After washing the agarose four times with TBS/Ca/tw, the proteins captured on the agarose were eluted with 50 µl of 1X SDS-PAGE loading buffer with or without 2-ME. Eluted samples were separated by SDS-PAGE followed by blotting to polyvinylidene fluoride membrane (Immobilon P; Millipore) in a semidyim system (Bio-Rad). The blotted membranes were then subjected to standard Western blotting. Briefly, the membrane was incubated with anti-MASP-1 or anti-MASP-2 Abs and then with HRP-conjugated anti-rabbit IgG (DakoCytomation). Proteins were detected using the ECL Plus Western blotting detection system (GE Healthcare Biosciences) and visualized in a LAS3000 (Fuji Film).

C4-deposition on mannan-coated microtiter plates

MaxiSorp surface of FluoloNunc plates (Nunc) were coated with 100 µl of 10 µg/ml mannan in sodium carbonate buffer (pH 9.6) soaked overnight. Blocking was done by adding 1% BSA in TBS buffer. Serially diluted murine serum in GVB buffer containing 1% BSA (GVB/BSA) was added to mannan-coated wells. After incubation for the indicated periods, the wells were washed four times with TBS/Ca/tw buffer. Each well was incubated with diluted purified human C4, at a final concentration of 5 µg/ml in GVB/BSA buffer at 37°C for 30 min, and then washed four times with TBS/Ca/tw buffer. The wells were incubated at 37°C for 30 min with FITC-conjugated anti-human C4 Ab (MP Biomedicals), followed by washing wells with TBS/Ca/tw buffer. Fluorescence intensity was detected by DTX800 multimode detector (Beckman Coulter) using filters (485 nm for excitation and 535 nm for emission). Integration time was 0.4 s.

C3-deposition on mannan-coated microtiter plates

Mannan-coated Maxi-Plates, prepared as described above, were blocked in TBS/Ca buffer containing 0.1% human serum albumin. Murine serum was diluted with BBS buffer (4 mM barbitol and 140 mM NaCl (pH 7.4)) containing 0.1% human serum albumin, 5 mM CaCl2, and 5 mM MgCl2. Diluted sera were incubated in mannan-coated wells at 37°C. Protein binding was stopped by adding 0.2 ml of BBS buffer containing 10 mM EDTA. C3 deposited on well surfaces was detected by anti-human C3c Ab (DakoCytomation) and HRP-conjugated secondary Ab; color was detected as described above.

Flow cytometry analysis of C3 deposition on zymosan particles

A total of 10% murine sera were incubated with 10 µg of zymosan A particles. Reaction was stopped by TBS containing 10 mM EDTA buffer. Deposited C3 was stained with anti-human C3c (DakoCytomation), biotinylated secondary Ab, and FITC-conjugated streptavidin on ice. Acquisitions were conducted by FACS Calibur (BD Biosciences).

Results

Generation of MASP1/3 knockout mouse

To assess the roles of MASP-1 and MASP-3 in vivo, we established a gene targeted mouse that lacks both MASP-1 and MASP-3. The MASP1/3 gene has 10 exons that encode the H chain common to both MASP1 and MASP3. A targeting vector was constructed to replace the second exon with a neomycin resistant gene cassette (Fig. 1A). Finally, four neomycin-resistant ES clones were obtained, in which the homologous recombination events were confirmed by Southern blotting analysis. Two of these were independently injected into C57BL/6 blastocysts, and the founder chimeras were bred with C57BL/6J females. Southern blotting analysis of tail DNA from agouti-color pups showed germline transmission of the targeted allele (Fig. 1B).

Flow cytometry analysis of C3 deposition on zymosan particles

A total of 10% murine sera were incubated with 10 µg of zymosan A particles. Reaction was stopped by TBS containing 10 mM EDTA buffer. Deposited C3 was stained with anti-human C3c (DakoCytomation), biotinylated secondary Ab, and FITC-conjugated streptavidin on ice. Acquisitions were conducted by FACS Calibur (BD Biosciences).

FIGURE 2. MASP-1 and MASP-3 are completely absent in MASP1/3−/− serum. A, Mouse sera from MASP1/3+/+ ( ), MASP1/3−/− (○), and MASP1/3−/− (□) were incubated in mannan-coated microtiter wells at 37°C for 30 min. MASP-1 captured on wells was detected by rabbit anti-MASP-1 and HRP-conjugated anti-IgG. B, A total of 20 µl of sera from MASP1/3+/+ (lane 1), MASP1/3−/− (lane 2), and MASP1/3−/− (lane 3) mice was incubated with mannan agarose for 30 min, and the bound fractions were subjected to Western blotting with anti-MASP-1 Ab under non-reducing conditions. (p) and (a) indicate the zymogen and the active-form of MASP-1, respectively. In lane 4, rMASP-1i was used as a control. C, RT-PCR for murine MASP3 mRNA. Forward primers were common to MASP1 and MASP3 transcripts, and reverse primers were specific for the L chain of MASP3. RT-PCR was nested using a primer set of 1F/1R for the MASP1/3 cassette (Fig. 1C). Finally, four neomycin-resistant ES clones were obtained, in which the homologous recombination events were confirmed by Southern blotting analysis.
MASP1/3−/− mice (from 4 to 10 wk old) were significantly smaller than control mice (p < 0.01, Student t test), although they showed no abnormality in either macroscopic appearance or microscopic analysis (data not shown). The average body weights of males at 6 wk of age were 20.8 ± 1.97 g (+/+), 21.1 ± 1.34 g (+/−), and 16.8 ± 1.66 g (−/−) (p = 0.0004, compared with +/+). and those of females were 17.9 ± 1.16 g (+/+), 17.5 ± 2.38 g (+/−), and 14.8 ± 1.73 g (−/−) (p < 0.0001, compared with +/+). The frequency of MASP1/3−/− mice developed by intercrossing of MASP1/3−/− was slightly lower (+/+: +/−: −/− = 114: 223: 63) than the expected frequency. Although MASP1/3−/− mice were fertile, the pups resulting from an intercross of MASP1/3−/− mice were more vulnerable. A possible reason is that nursing MASP1- and MASP3-deficient mothers are too small to provide sufficient milk. Two strains, derived from two independently targeted ES clones, showed the same body weight phenotype and similar frequencies of homozygous pups. This excludes the possibility that another gene locus is additionally disrupted. These data suggest that MASP1- and/or MASP3 might be involved, in part, in development and growth.

MASP-1 and MASP-3 are completely absent in MASP1/3−/− mice

To investigate whether MASP-1 is entirely absent in MASP1/3−/− mice, the amount of MASP-1 in mouse serum was estimated by an ELISA system using an anti-mouse MASP-1 Ab. As shown in Fig. 2A, no MASP-1 was detected by this method in the serum of MASP1/3−/− mice, whereas MASP-1 in the sera of MASP1/3+/+ and MASP1/3−/− mice was captured in a dose-dependent manner. In another experiment, MBL-MASP complexes in mouse serum were pulled down with mannan-agarose. By Western blotting of the complexes with anti-mouse MASP-1 under nonreducing conditions, both the active form and the proenzyme form of MASP-1 were found in MASP1-expressing mice (MASP1/3+/+ and MASP1/3−/−) (Fig. 2B, lanes 1 and 2, respectively). However, no detectable band derived from MASP-1 was observed in MASP1/3−/− mice (lane 3). Several additional bands (100, 140, and 200 kDa) were also detected in the serum of MASP1/3−/−. They might be MASP-3 itself or complexes with serine protease inhibitors, such as C1 esterase inhibitor or α2-macroglobulin, although they have not yet been identified. These results confirmed that MASP-1 protein was completely absent from MASP1/3−/− mice.

To assess whether or not MASP-3 is present in MASP1/3−/− mice, RT-PCR of murine MASP3 was conducted, because our attempt failed to generate a high enough titer of Ab against the L chain of MASP-3. Using liver cDNA from wild-type mouse as a template, a 1415 bp cDNA fragment spanning both the H and L chain coding regions of MASP3 was specifically amplified; however, no such product could be amplified from the liver cDNA of MASP1/3−/− mice (Fig. 2C). These results suggest that not only MASP-1, but also MASP-3, is absent in MASP1/3−/− mice.
MASP1/3−/− mice show low C4 cleavage ability associated with low MASP-2 activation

To assess the activity of the lectin pathway in MASP1/3−/− mice, we conducted the C4-deposition assay with mannan-coated plates as described in Materials and Methods. Using sera from MASP1/3+/+/ mice, the amount of C4-deposition on mannan-coated plates increased in a dose-dependent manner (Fig. 4B). In contrast, C4-deposition from the sera of MASP1/3−/− mice was significantly lower than that in MASP1/3+/+/ mice. Kinetics plots of C4-deposition using 5 μl of serum showed a very low activity in MASP1/3−/− mice (Fig. 3B). These results support the possibility that MASP-1 or MASP-3 is involved in the activation of the lectin complement pathway. To determine whether lack of MASP-1 contributes to the reduced activity of complement activation in MASP1/3−/− mice, recombinant mouse MASP-1K was added to the serum. rMASP-1K was modified from native-type of MASP-1 by replacing the arginine residue at the reactive site P1 for activation of MASP-1 with lysine. The same strategy was conducted when recombinant MASP-2 was expressed by Chen and Wallis (22). Their mutant MASP-2K reduced the rate of its autoactivation during synthesis and purification. We have attempted to produce recombinant native-type of mouse MASP-1 by baculovirus expression system, but very poor protein could be purified. Instead of the native type of MASP-1, a large amount of rMASP-1K could be purified from a high five cell line that was stably transfected with an expression vector. The C4-deposition activity of MASP1/3−/− mouse serum was restored by the reconstitution of rMASP-1K (Fig. 3B).

In the lectin pathway, it has been well known that MASP-2 cleaves C4 and C2. Next, we asked whether MASP-2 was activated in the absence of MASP-1. MBL-MASP complex was captured by mannan-agarose from mouse serum diluted with TBS/Ca buffer, and subsequently subjected to Western blotting using an Ab recognizing the H chain of MASP-2. Aprotinin was able to prevent the activation of MASP-2 completely in MBL complexes derived from sera of MASP1/3+/+ and MASP1/3−/− (Fig. 4A). The level of proenzyme form of MASP-2 (88 kDa) in serum of MASP1/3−/− was comparable with that in serum of MASP1/3+/+, suggesting that the concentrations of MASP-2 in both sera were not different. When serum of MASP1/3+/+ mice was incubated in the absence of aprotinin, a band of 62 kDa corresponding active form of MASP-2 was detected, in addition to an 88 kDa band corresponding to the proenzyme form of MASP-2 (Fig. 4B). The bands of ~20 kDa seen in all lanes were the murine counterpart of human sMAP, a truncated form of MASP-2. In MBL-MASP complex from MASP1/3+/+ mice, the active form of MASP-2 was observed following 10, 20, and 45 min of incubation with mannan-agarose (Fig. 4B, lanes 2, 4, and 6). In contrast, MASP-1- and MASP-3-deficient mice revealed no active form of MASP-2 following up to 20 min of incubation with mannan-agarose (lanes 1 and 3). MASP-2 was converted to the activated form after 30 min; however, the amount of active MASP-2 in MASP1/3−/− mice was lower than that in MASP1/3+/+ mice. Addition of rMASP-1n into the sera of MASP1/3−/− mice restored the MASP-2 activation (Fig. 4C).

Cleavage of recombinant inactive MASP-2 mutant (rMASP-2I) by rMASP-1K

To assess whether MASP-1 cleaves MASP-2 directly, we incubated a recombinant mutant of MASP-2, rMASP-2I, with rMASP-1K. Previous studies have shown that rMASP-2 was easily autoactivated during its preparation (13). Therefore, we used rMASP-2I as a ligand. This mutant was not cleaved by itself because it lacks protease activity. As shown in Fig. 5, rMASP-1K did not cleave rMASP-2I directly. In contrast, rMASP-1l could not cleave rMASP-2I, even if the concentration of rMASP-1l was more than 2-fold higher than that of rMASP-1K, indicating the specific activity of rMASP-1K.

MASP1/3−/− mice show low C3 cleavage ability

To assess C3 activation by the lectin pathway in mouse serum, diluted serum was incubated with mannan-coated plates, and deposited endogenous C3 was determined using an anti-C3c Ab. C3 activation
deposition from the sera of MASP1/3–/– mice was much lower than C3 deposition from the sera of MASP1/3+/+ mice (Fig. 6A). The kinetics of C3 activation by 2 μl of serum was very slow in MASP1/3–/– mice (Fig. 6B). By adding rMASP-1K into the serum of MASP1/3–/– mice, the C3-deposition activity was restored.

We also examined C3 activation by yeast-derived-zymosan particles. When zymosan particles were incubated with normal murine serum, the significant C3 deposition on the particles was observed for 1-min incubation (Fig. 7A). This activity was almost inhibited by adding 0.1 M mannose. Further incubation (5 min) allowed the C3 deposition on the particles by normal murine serum even if adding mannose (Fig. 7B). These results suggested that the lectin pathway plays an important role in the early event for complement activation on zymosan surface, although alternative pathway might be mainly involved in the late complement activation. In MASP1/3–/– serum, there was no C3 deposition on zymosan particles for 1-min incubation (Fig. 7C). rMASP-1n, but not rMASP-1i, could increase the C3 deposition activity in serum of MASP1/3–/– for 1-min incubation (Fig. 7D).

Discussion
We have generated mice deficient in MASP-1 and MASP-3 by gene targeting, and have used these mice to investigate the role of MASP-1 in the activation of the lectin complement pathway.

Among MASP-1, MASP-2, and MASP-3, only MASP-2 has C4 cleavage activity (8, 12). A number of studies in vitro supported the possibility that MASP-2 alone is sufficient to activate complement in the absence of MASP-1 and MASP-3. Surprisingly, however, serum derived from MASP1/3–/– has a decreased ability to activate C4 on mannan-coated microtiter wells. No activation of MASP-2 was observed in MASP-1- and MASP-3-deficient serum, when serum was incubated with mannan-agarose for 10 min, whereas activation of MASP-2 was observed in MASP-1- and MASP-3-containing serum (Fig. 4). rMASP-1K restored C4 and MASP-2 activation in MASP-1- and MASP-3-deficient serum (Figs. 3 and 4). These results support the possibility that MASP-1 also contributes to the activation of the lectin pathway at the step of MASP-2 activation.

The precise mechanism by which MASP-1 affects the activation of MASP-2 is not clear. One possible explanation is that MASP-1 cleaves MASP-2 directly. To verify this possibility, we incubated a mutant of rMASP-2i with rMASP-1K. As shown in Fig. 5, it was confirmed that rMASP-1K possesses activity to cleave rMASP-2i in vitro. Another possibility is that MASP-1 enhances the autoactivation of MASP-2. In any case, it has been previously reported that the complex of MASP-1 contains MBL and sMAP, but not MASP-2, using an immunoprecipitation assay with an anti-MASP-1 Ab (23). So far, there is no evidence that MASP-1 and MASP-2 associate with each other in an oligomer of MBL. In peripheral blood, MBL may form individual complexes with MASP-1, MASP-2, or MASP-3, respectively. When these MBL/MASPs complexes bind to carbohydrates on microorganisms, it is possible that in the vicinity of this binding, MBL/MASP-1 may interact with MBL/MASP-2.

MASP-2 was activated even in the absence of MASP-1 and MASP-3, when the serum was incubated with mannan for >30 min (Fig. 4). It has been reported that rMASP-2 is easily autoactivated and rMASP-2 alone associated with MBL is sufficient for adding 0.1 M mannose. C. Comparison of C3 deposition activity between serum of C57BL/6 (opened histogram) and that of MASP1/3–/– (filled histogram). D. MASP1/3–/– serum (grayed histogram) was reconstituted with 100 ng of rMASP-1n (solid line) and 300 ng of rMASP-1i (mutant type) (dot line). Incubation time was 1 min.
the activation of C4 (13). However, we would like to point out the fact that MASP-2 circulates as a zymogen in peripheral blood, suggesting that some unknown mechanism prevents autoactivation of MASP-2. A possible explanation is that a physiological conformational change in MBL structure may alter the stability of MASP-2, as reported by Wallis (24). Under physiological conditions, MASP-1 may affect the structure or stability of the MBL-MASP-2 complex, thereby resulting in activation of MASP-2.

We also investigated the deposition of C3 from murine serum onto mannan. All complement pathways contribute C3 cleavage to form C3b and C3a that have important roles in the proceeding complement cascades. In MASP-1- and MASP-3-deficient serum, a significantly lower amount of C3 deposition was observed than that in MASP-1- and MASP-3-containing serum. No significant difference of concentrations of C3 and C4 between wild-type and MASP-1/3-deficient sera was observed (data not shown). MASP-1 and MASP-3-deficient serum has decreased activity to form a C3 convertase, C4b2a, supporting the possibility that C3 deposition from MASP-1- and MASP-3-deficient serum was also lower. From several reports, it is clear that MASP-1 can cleave C2 (12, 22). In addition to MASP-2, therefore, MASP-1 activates C2 and also plays an important role in the formation of the C3 convertase, C4b2a. The other possible explanation is that MASP-1 directly activates C3, as reported previously in human, although this C3 cleaving activity is questioned (15, 16). We now have mice deficient for all MASP proteins in our laboratory, and this question is currently under investigation.

MASP1 and MASP3 mRNA were transcribed from same gene by alternative splicing. A common exon between them has been targeted for disruption to make the knockout mice. It has been shown that MASP-3 was also absent in these mice. Therefore, the affect of deficiency of MASP-3 in MASP1/3−/− mice could not be eliminated. However, Dahl et al. (9) has reported that MASP-3 inhibited the activation of C4 and MASP-2, suggesting that MASP-3 may negatively regulate the lectin pathway. Furthermore, rMASP-1K could completely restore the activation of C4 and C3 in MASP1/3−/− mice. All together, at least positive effects of MASP-1 in the lectin pathway can be concluded from our study, although effect of MASP-3 should be discussed in future study.

In conclusion, we generated MASP-1- and MASP-3-deficient mice, and found that MASP-1 plays a pivotal role in the activation of the lectin pathway, probably through activation of MASP-2.

Disclosures

The authors have no financial conflict of interest.

References