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Mice Deficient in Ficolin, a Lectin Complement Pathway Recognition Molecule, Are Susceptible to Streptococcus pneumoniae Infection

Yuichi Endo,* Minoru Takahashi,* Daisuke Iwaki,* Yumi Ishida,* Naomi Nakazawa,* Toshihisa Kodama,* Tomohiro Matsuzaka,* Kazuko Kanno,* Yu Liu,* Kohsuke Tsuchiya, † Ikuo Kawamura, † Masahito Ikawa, ‡ Satoshi Waguri, § Ikuo Wada, ¶ Misao Matsushita, ¶ Wilhelm J. Schwaebel, # and Teizo Fujita*

Mannose-binding lectin (MBL) and ficolin are complexed with MBL-associated serine proteases, key enzymes of complement activation via the lectin pathway, and act as soluble pattern recognition molecules in the innate immune system. Although numerous reports have revealed the importance of MBL in infectious diseases and autoimmune disorders, the role of ficolin is still unclear. To define the specific role of ficolin in vivo, we generated model mice deficient in ficolin. The ficolin A (Fcna)-deficient (Fcna−/−) and FcnA/ficolin B double-deficient (Fcna−/− b−/−) mice lacked FcnA-mediated complement activation in the sera, because of the absence of complexes comprising FcnA and MBL-associated serine proteases. When the host defense was evaluated by transnasal infection with a Streptococcus pneumoniae strain, which was recognized by ficolins, but not by MBLS, the survival rate was significantly reduced in all three ficolin-deficient (Fcna−/−, Fcnb−/−, and Fcn−/− b−/−) mice compared with wild-type mice. Reconstitution of the FcnA-mediated lectin pathway in vivo improved survival rate in Fcn−/− but not in Fcn−/− b−/− mice, suggesting that both FcnA and ficolin B are essential in defense against S. pneumoniae. These results suggest that ficolins play a crucial role in innate immunity against pneumococcal infection through the lectin complement pathway. The Journal of Immunology, 2012, 189: 5860–5866.

The complement system plays a crucial role in protecting against invading microorganisms through three activation pathways: the classical, alternative, and lectin pathways. These activation routes focus to activate the central complement component C3, and finally mediate many immune responses including opsonization, phagocytosis, cytokine production, and chemotaxis. Model animals deficient in complement components have provided evidence for the roles of the classical and alternative pathways in protection against microorganisms (1, 2). The lectin pathway, the third pathway of complement activation, is thought to be working as the first-line host defense in innate immunity (3, 4).

In mammals, three kinds of recognition molecules for the lectin pathway have been identified: mannose-binding lectin (MBL), ficolin, and collectin 11/collectin kidney 1 (5–7). These molecules act as pattern recognition molecules and recognize pathogen-associated molecular patterns on the surface of microorganisms and aberrant carbohydrate structures on the surfaces of apoptotic, necrotic, and malignant cells. Almost all of these molecules form complexes with three MBL-associated serine proteases (MASPs): MASP-1, MASP-2, and MASP-3 (8–10). They also interact with small MBL-associated protein (sMAP)/Map19, which is a truncated splicing product generated by MASP2 gene and lacks protease activity (11, 12). Targeted recognition of the complexes induces the activation of MASPs, and, in turn, MASP-2 cleaves C4 and C2 to generate C4b2a, a C3 convertase, and MASP-1 and MASP-3 activate factors D and B to initiate the alternative pathway, an amplification loop of C3 activation (13, 14). Although MBL has been intensively investigated by using MBL-deficient and MBL-null mice (4, 15), the in vivo role of ficolin remains unclear, mainly because of the lack of an experimental animal model in combination with a ficolin-specific pathogen.

Ficolin is a unique lectin in that it has a C-terminal fibrinogen-like domain that is responsible for carbohydrate recognition (16, 17). Ficolin–MASPs complexes initiate the ficolin-mediated lectin pathway, which appears to be independent of the MBL-mediated lectin pathway driven by the MBL–MASPs complexes. To date, three and two ficolins have been identified in humans and mice, respectively. Comparing their phylogenetic and biochemical properties, it was found that human ficolins are related to murine
ficolins. More specifically, human M-ficolin (M-FCN, FCN-1) is the ortholog of murine ficolin B (FcnB); Human L-ficolin (L-FCN, FCN-2) is closely related to murine ficolin A (FcnA), although the genes encoding these ficolins are suggested to have evolved independently in each murine and primate lineage, respectively (18). The H-ficolin (H-FCN, FCN-3) gene (FCN3) is a pseudogene in the murine lineage. Accumulating data indicate that each ficolin recognizes an overlapping spectrum of microorganisms (5, 6, 19, 20), and that the deficiency and/or low level of human ficolins has been associated with specific infectious diseases (21–23).

To evaluate the contribution of ficolins in innate immunity, we generated three mouse lineages deficient in ficolins in this study. Based on the observations of their in vitro and in vivo phenotypes, we provide in this study the first evidence, to our knowledge, that the ficolin-mediated lectin pathway plays an essential role in protection against Streptococcus pneumoniae infection that is a major cause of pneumonia, septicaemia, otitis media sinusitis, and meningitis.

Materials and Methods

Mice

Fcna-deficient (Fena+/−) and Fcnb-deficient (Fcnb−/−) mouse lineages were generated using the standard protocol of gene targeting (Supplemental Fig. 1). Targeted embryonic stem cells (129SV) were implanted into mouse C57BL/6J blastocysts to generate chimeric mice. Finally, intercrossing respective F2 heterozygous offspring was used to produce homozygous Fena−/− and Fcnb−/− mice. These knockout mice were backcrossed to C57BL/6J, and Fena+/− and Fcnb−/− mice used in this study were in 15th and 10th filial generations, respectively.

Double-heterozygous Fena−/−b+/− mice carrying the haplotype Fena−/−b+ were interbred to generate a line of FcnA/FcnB double-deficient (Fena−/−b−/−) mice. As previously reported (18), the Fena and Fcnb genes are located on the same chromosome (2A3). Therefore, Fena+/−b+− and Fena−/−b+− mice were initially crossbred to generate an offspring carrying haplotype Fena−b+. The obtained double-heterozygous mice carrying genotype Fena−/−b−/−a−/− were then interbred to generate the Fena−/−b−/− offspring.

Transiently FcnA-expressing Fena+/− and Fena−/−b+− mice were produced using a piggyBac transposon-mediated long-term gene expression system (24). In brief, FcnA cDNA was constructed in a plasmid pIRCMV expression system with the pMT/Bip/V5-His A vector (Invitrogen, Carlsbad, CA) as transfection vector (25). Recombinant FcnB (rFcNB) was produced in the CHO-S-SFM (Life Technologies, Grand Island, NY) culture media (CHO-S-SFM; Life Technologies, Grand Island, NY) was prepared as described earlier. The mice were then washed extensively with TBS-Ca and subjected to Western blotting. Western blotting was performed under reducing conditions using the primary Abs against FcnA and FcnB (25), MASP-1 (26), MASP-2 (27), MBL-A, and MBL-C (Hy Cult Biotechnology, Uden, The Netherlands) as described previously. Signals were detected by further incubation with HRP-conjugated secondary Abs (DakoCytomation, Glostrup, Denmark), avidin-biotinylated HRP complex, and ECL. Chemiluminescence image was observed in an LAS-3000 (Fujiﬁlm, Tokyo, Japan).

Binding assay

Binding of the recombinant lectins (rFena, rFcNB, MB-L-A, and MB-L-C) to S. pneumoniae D39 strain (NCTC 7466) was assessed as follows: heat-killed bacteria (1 × 106 cells) were incubated with 0.5 μg of the recombinants in 100 μl TBS-CaT containing 3% BSA at 4°C for 1 h. The bacteria were then washed extensively with TBS-CaT and subjected to Western blotting. Binding speciﬁcity was conﬁrmed by incubation with 150 mM GlcNAc.

Complement activation assay

C4-deposition assay was used to evaluate complement activation via the lectin pathway as previously described (25, 27). In brief, mouse serum, mannosel-ulate, or GlcNAc-elaye was incubated on a GlcNAc-Ba-coated microtiter plate in 100 μl TBS-Ca at 37°C for 10 min. Plates were further incubated with human C4 at 4°C for 30 min, and the bound C4b was detected with HRP-sheep anti-human C4 Ab (Biogenesis, Poole, U.K.). C4b was developed by incubation with 3.3',5'-tetramethylbenzidine and H2O2 for 5–60 min at room temperature and monitored as described earlier. The activity was expressed as absorbance at 450 nm at 5-min incubation.

Infection

S. pneumoniae D39 strain was inoculated onto blood agar plates for 20 h in a CO2 incubator, and the colonies were collected and suspended in brain–heart infusion broth (Nikon Biomedical Laboratory, Kyot, Japan). The number of bacteria in the solution was calculated as 1 × 106 CFU/ml at an OD of 38 at 600 nm. Male mice (12–13 wk old) were anesthetized with pentobarbital. After 20 min, 20 μl bacteria solution (3.3 × 106 CFU) in brain–heart infusion broth was pipetted onto the nose of each mouse. In a preliminary experiment, the survival of wild-type (WT) mice was assessed using various doses of pathogen (Supplemental Fig. 2). In another experiment, mice with transiently FcnA-expressing Fena−/−b−/− mice prepared as described earlier, 2 d after plasmid injection, the mice were infected with 3.3 × 106 CFU. Mouse survival was counted every 24 h for >7 d.
Viable bacteria counts in the lungs were determined by sacrificing the mice 3 d postinfection. After drawing blood from heart of anesthetized mouse, the lungs were collected, weighted, and homogenized in 4 vol PBS in a tissue homogenizer (TH115; Omni International, Kennesaw, GA). Viable bacteria counts were determined by inoculating the serial dilutions of the lung homogenate on blood agar plates.

Statistics

The difference in C4- and C3-deposition level was evaluated by Student t test. The difference in survival rate in pneumococcal infection was evaluated by Pearson’s χ² test.

Results

General phenotypes of ficolin-deficient mice

No abnormality was observed in three ficolin-deficient mouse lineages, Fcna−/−, Fcnb−/−, and Fcna−/−b−/− mice, in their appearance, body weights, and reproductive fitness (data not shown). Specific abnormalities were also not observed in the tissues from the adult mice of these lineages, including the liver, spleen, lung, and bone marrow. In addition, no significant difference was observed in the peripheral blood cell counts and coagulation time between these knockout and WT mice.

Reduced activity of the lectin pathway in Fcna−/− and Fcna−/−b−/− mice

Fcna levels were estimated to be 3.50 ± 0.58 and 1.77 ± 0.24 μg/ml (mean ± SD) in the sera from WT and heterozygous Fcna+/− mice, respectively, whereas no FcnA was detected in the homozygous Fcna−/− mice (Fig. 1A). FcnB was detected in the bone marrow, a major expression site in mice, instead of WT and Fcnb−/− mice (Fig. 1B). FcnB was also detected in the circulation of Fcna−/− mice at a low average concentration of 130 ng/ml serum, although it was not detected in the Fcna−/−b−/− sera (Fig. 1C). To avoid complications resulting from the copresence of large amounts of Fcna, we assessed Fcna−/− and Fcna−/−b−/− sera instead of WT and Fcnb−/− sera, respectively, for the FcnB ELISA. C4-deposition activities of Fcna−/− and Fcna−/−b−/− sera were significantly lower than that of WT sera (Fig. 1D), suggesting a deficiency in the activity driven by FcnA. In contrast, the activity of Fcnb−/− sera was comparable with WT, suggesting that the activity of FcnB was too low to contribute to the lectin pathway in the circulation, at least under normal conditions.

To further characterize complement activation by FcnA, we subjected mouse serum to GlcNAc-agarose affinity chromatography to separate ficolins from MBLs. FcnA was recovered in the GlcNAc-eluates of WT and heterozygous Fcna+/− mice, whereas MBLs were in the mannose-eluates of WT, Fcna−/−, and Fcna−/− mice at similar levels (Fig. 2A). The substantial amounts of MASP-1, MASP-2, and sMAP were recovered in the mannose-eluate of WT, whereas only trace amounts were recovered in the GlcNAc-eluate (Fig. 2C). They were not detected in the GlcNAc-eluate from Fcna−/− mice. Consistently, C4-deposition activity of the GlcNAc-eluate was significantly lower in Fcna−/− than in WT mice, whereas the activity of mannose-eluates was not different among the three genotypes (Fig. 2B). These results indicate that FcnB−/− mice lack FcnA-mediated C4 deposition because of the lack of FcnA-MASPs-sMAP complexes; however, they have a normal MBL-mediated C4 deposition in the sera. As shown in Fig. 2C, addition of an excess amount of rFcna into the Fcna−/− serum recovered MASP-1, MASP-2, and sMAP in the GlcNAc-eluate. This eluate exhibited a comparable or rather higher C4-deposition activity than that of the WT (Fig. 2D). Thus, Fcna−/− and Fcna−/−b−/−, but not Fcnb−/− mice demonstrated reduced activities of C4 deposition in the sera, because of the lack of complexes comprising FcnA and MASPs.

Role of FcnB in complement activation

GlcNAc-agarose chromatography of the sera revealed that FcnB was recovered in the GlcNAc-eluate of Fcna−/−, but not in Fcnb−/−b−/−, confirming that FcnB is present in the circulation (Fig. 2E). Consistently, C4-deposition activity was significantly higher in the GlcNAc-eluate from Fcna−/− than that from Fcna−/−b−/−, although the observed activity was on the border of detectable level (Fig. 2F). Complex formation of FcnB with MASP-2 and sMAP was confirmed by a pull-down of the complex after the addition of rFcnaB to Fcna−/−b−/− serum (Fig. 2G). This result was further confirmed by our recent study, where FcnB formed the complexes with the recombinant MASP-2 and recombinant sMAP, and the formed rFcnaB–recombinant MASP-2 complex activated C4 on GlcNAc-coated plates (28). A similar result was recently reported in which the rat rFcnaB activated MASP-2 on the immobilized GlcNAc (29). These results suggest that FcnB is capable of forming complexes with MASP-2 and sMAP, and that the FcnB-mediated complement activation might occur at the inflammatory sites rather than in the normal circulation.

FIGURE 1. Ficolin levels and C4-deposition activities in ficolin-deficient mice. (A) FcnA levels estimated by ELISA in WT, Fcna−/− (A+/−), and Fcna−/− (A−/−) mouse sera. Horizontal and dotted lines depict the mean level and threshold of the detectable level, respectively. Open and closed circles denote male and female individuals, respectively. (B) FcnB levels estimated by Western blotting in the bone marrow cells from WT, Fcnb−/− (B+/−), and Fcnb−/− (B−/−) mice. Bone marrow cells sonicated in 10-fold volume of PBS containing 1% Tween X-100 and 5% protease inhibitor were centrifuged at 12,000 rpm, and 25 μl of the supernatant was subjected to Western blotting. (C) FcnB levels in the sera from Fcna−/− (A−/−) and Fcna−/−b−/− (A−/−B−/−) mice as estimated by an ELISA. Horizontal and dotted lines depict the mean level and threshold of the detectable level, respectively. (D) C4-deposition activities of 0.75 μl sera from WT, Fcna−/−, Fcna−/−, Fcnb−/−, and Fcna−/−b−/− mice on GlcNAc-coated plates.
Defensive role of ficolins against S. pneumoniae infection

The D39 strain of *S. pneumoniae* was recognized by rFcnA and rFcnB, and very weakly recognized by rMBL-A, but not by rMBL-C (Fig. 3A). Binding of rFcnA and rFcnB was inhibited, in part, by the presence of GlcNAc, suggesting specificity via their fibrinogen domains. The activity of mouse sera to opsonize this bacterium was determined using the C3-deposition assay. *Fcnα−/−* and *Fcnα−/−b−/−* sera showed significantly lower activities than WT sera (Fig. 3B), which was consistent with the C4-deposition activity results (Fig. 1D). Based on these results, we next established an experimental infection with *S. pneumoniae* D39 strain, where the nasal dose was fixed at $3.3 \times 10^6$ CFU to achieve ~80% survival rate of WT mice (Supplemental Fig. 2). Knockout and some WT mice died within 3–5 d postinfection (Fig. 3C). The survival rate was significantly lower than the WT in all three ficolin-deficient (*Fcnα−/−*, *Fcnβ−/−*, *Fcnα−/−b−/−*) lineages. Viable counts of bacteria in the lung homogenates were widely ranged up to $>2 \times 10^7$ CFU per 10 mg lung tissue in the 3 ficolin-deficient mice. The average counts were much higher by one order magnitude than that in WT mice, although the statistics did not reach significance in the *Fcnα−/−* mice (Fig. 3D).

Fcna was transiently expressed in vivo in *Fcnα−/−* and *Fcnα−/−b−/−* mice by i.v. injecting Fcna-encoding pIRCMV plasmid before the mice were infected with *S. pneumoniae* to further confirm the defensive role of ficolins. Fcna was produced at significant amounts in the sera for at least 6 d after infection (Fig. 4A). GlcNAc-agarose chromatography revealed that the transiently expressed Fcna was recovered in the GlcNAc-eluate, together with MASP-2 and sMAP, suggesting reconstruction of the Fcna–MASPs–sMAP complexes in the sera (Fig. 4B). The same GlcNAc-eluate showed a comparable C4-deposition activity with that of the WT (Fig. 4C). Finally, the survival against infection was comparatively evaluated between the mice injected with both pRCMV and pFerH plasmids and the mice infected with pFerH alone. *Fcnα−/−* mice injected with both plasmids exhibited a significantly higher survival rate, which was comparable with that of the WT (Fig. 4D). As shown in Fig. 4E, however, *Fcnα−/−b−/−* mice injected with both plasmids did not show a significantly improved survival rate as compared with the mice injected only with pFerH plasmid. These results suggest that both Fcna and Fcnb are essential for defense against *S. pneumoniae* D39 infection.

**Discussion**

In this study, we found that the circulating Fcna works to protect against *S. pneumoniae* infection via the lectin pathway, because the deficiency of the Fcna-mediated lectin pathway resulted in a reduced survival rate of infected animals, and its in vivo reconstitution resulted in the improved survival. The Fcna-mediated lectin pathway appears to be independent of the MBL-mediated lectin pathway.
lectin pathway, because MBL-mediated C4 deposition driven by MBL–MASPs–sMAP complexes was detected at similar levels in Fcna−/− and WT mice (Fig. 2B). Therefore, it is clear that FcnA predominantly plays a defensive role in protection against S. pneumoniae. Although MBLs are the major initiators of the lectin pathway, our data suggest that they are not involved in pneumococcal infection. This is also supported by a limited role of MBL in pneumococcal pneumonia in humans (30). No association was reported between human FCN2 gene polymorphisms leading to low serum levels of L-FCN (human counterpart of FcnA) and pneumococcal infectious disorders (31). This suggests that half of the ficolin levels observed in the heterozygous state might be sufficient to fight S. pneumoniae. Taken together, it is suggested that the FcnA-mediated lectin pathway specifically serves as a surveillance system against pneumococcal infection. Recently, it was reported that MASP-2–deficient mice failed to opsonize S. pneumoniae, suggesting that in addition to FcnA, MASP-2 is also essential for defense against S. pneumoniae (32). It was also reported that the Fcna−/− mice were susceptible to infection with another microbe, influenza A virus (33).

Fcna is a plasma/serum-type ficolin, which is mainly expressed in the liver, suggesting that FcnA plays its defensive role in the circulation. It is possible that FcnA has a latent defensive ability in the lung, because the Fcna gene is expressed at low level in the lung (34). Expression of the Fcna gene in tissues overlaps to that of the FCN2 gene (35). This study confirmed that the serum concentration of FcnA was also similar to that of L-FCN, which was reported to be an average of 3.7 μg/ml (36). These results predict that the deficiency of L-FCN would result in increased susceptibility to pneumococcal infection in humans. No case with complete L-FCN deficiency has been reported so far.

Another important finding is that infected Fcnb−/− mice also showed a lower survival rate as described earlier. The defensive role of FcnB was confirmed by no significant improvement of survival rate in the transiently FcnA-expressing Fcna−/−b−/− mice. In comparison with the full improvement of survival in the transiently FcnA-expressed Fcna−/− mice, this result clearly suggests that FcnB is also essential for defense against pneumococcal infection. In contrast, the complement activation activity of the Fcnb−/− sera was comparable with the WT sera (Figs. 1D, 3B). This result appears to be reasonable, because FcnB is a nonplasma/serum-type ficolin and detected in the serum at a trace amount (Fig. 1B). Several explanations are possible to explain the discrepancy between low survival rate in the Fcnb−/− mice and normal complement activation activity in their sera. First, it is known that FcnB expression is upregulated upon macrophage activation (37), and that the expression of M-FCN (human ortholog of FcnB) is induced several times in monocyte-derived macrophages after treatment with TLR2 and TLR4 ligands (38). Second, FcnB might execute its defensive function at the local site of lung rather than in the circulation. It is important to note that FcnB is produced in the myeloid cell lineage or in granulocytes (39, 40), and M-FCN is produced in and secreted from peripheral monocytes, macrophages, and neutrophils (6, 41). To date, there is no evidence that the Fcnb gene is expressed in the lung cells, although it is known that the FCN1 gene is expressed in the lung at a significant level (36, 42). Although the origin of FcnB in the circulation is unclear, it is possible that FcnB is produced in the infiltrated macrophages and granulocytes, and thereby explores its function at the local site of lung. Third, FcnB partially executes its function without complement activation via the lectin pathway. It is noteworthy that rFcnb produced in Drosophila S2 cells associated
to a lesser extent with MASPs, exhibited a strong activity to aggregate Staphylococcus aureus, and enhanced phagocytosis by phagocytes (43). This suggests that FcnB can potentially work more effectively via primitive opsonophagocytosis. This speculation might be supported by the observation that FcnB was colocalized with Lamp-1, a marker for lysosomes and late endosomes in macrophages (37). The orthology between FcnB and M-FCN predicts that M-FCN deficiency would result in the increased susceptibility to pneumococcal infection in humans. This study confirmed that the serum concentration of mouse FcnB was comparable with that of M-FCN, which was reported to be an average of 60.5 ng/ml (41).

It was previously reported that MBLs-null (MBL-A/MBL-C double-deficient) mice were susceptible to S. aureus infection (4). As described earlier, ficolins also recognized this pathogen and led to its opsonization with C3b (44). These results suggest that ficolins cooperate together with MBLs as defense molecules against S. aureus, which is not the case for S. pneumoniae infection. This study showed that FcnA and FcnB have a similar role against the same pathogen, suggesting that the two ficolins work cooperatively, at least not competitively, in protecting against pneumococcal infection. This is supported by insufficient improvement in survival rate of the transiently FcnA-expressing FcnA−/− mice. Furthermore, the difference between human and mouse in the lectin pathways should be noted: in humans, the serum concentrations of ficolins (mainly L-FCN plus H-FCN) are lower than MBLs (MBL-A plus MBL-C) (46). In addition, primates including humans have an additional ficolin, H-FCN, within their circulatory system. Although H-FCN recognizes a limited spectrum of bacteria (47), it was reported that an H-FCN-deficient patient suffered from recurrent infections (21). These evidences suggest that the ficolin-mediated lectin pathway is more active and more important in humans than in mice. Taking this into consideration, we propose that ficolins play the comparable roles with MBL in the lectin pathway, and that these roles are shared among ficolins themselves and between ficolin and MBL.

In conclusion, FcnA−/− and FcnA−/− FcnB−/− mice exhibited reduced survival rates when infected transnasally with S. pneumoniae D39 strain, and reconstitution of the ficolin-mediated lectin pathway in infected FcnA−/− mice resulted in improved survival rate. FcnB−/− mice also demonstrated reduced survival against the same bacterial infection. The defensive role of FcnB was confirmed by insufficient improvement of survival in the transiently FcnA-expressing FcnA−/− FcnB−/− mice. The defense mechanism of FcnB remains to be clarified. The susceptibility of the three ficolin-deficient mice against S. pneumoniae D39 was supported by higher viable counts of bacteria in their lungs. These results suggested that ficolins play a pivotal role in the protection against S. pneumoniae, which is the most common cause of bacterial pneumonia in children worldwide. It is noteworthy that ficolins are the predominant initiators of the lectin pathway activation and, therefore, the potential key molecules for pneumococcal infection.

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Disclosures

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