Antibody-Dependent Enhancement Occurs Upon Re-Infection with the Identical Serotype Virus in Feline Infectious Peritonitis Virus Infection

Tomomi TAKANO¹⁾, Chisako KAWAKAMI¹⁾, Shinji YAMADA¹⁾, Ryoichi SATOH¹⁾ and Tsutomu HOHDATSU^{1)*}

¹⁾Laboratory of Veterinary Infectious Disease, School of Veterinary Medicine, Kitasato University, Towada, Aomori 034-8628, Japan

(Received 9 June 2008/Accepted 22 August 2008)

ABSTRACT. Feline infectious peritonitis virus (FIPV) is classified into serotype I and serotype II according to the amino acid sequence of its spike(S) protein. Antibody dependent enhancement (ADE) of macrophage infection occurs in the presence of antibodies to FIPV S protein, and a close relationship between ADE and neutralizing epitopes has been reported. The importance of differences in FIPV serotype on the induction of ADE remains unclear. In this study, we investigated whether the same or different serotype of FIPV induces ADE in cats. Specific pathogen-free cats were passively immunized with anti-type I or II FIPV antibodies, and we investigated the induction of ADE following subcutaneous inoculation with type I FIPV. Inoculation using FIPV serotype I enhanced the onset of FIP in cats passively immunized with FIPV serotype I-specific antibodies but not in those passively immunized with antibodies to FIPV serotype II. These data suggest that re-infection with the same serotype induces ADE in cats infected with FIPV.

KEY WORDS: ADE, coronavirus, FIPV, serotype.

J. Vet. Med. Sci. 70(12): 1315–1321, 2008

Feline infectious peritonitis virus (FIPV), a feline coronavirus (FCoV) in the family *Coronaviridae*, causes fatal disease in wild and domestic cat species. FCoV is an enveloped virus with a single-stranded positive-sense RNA genome. The FCoV virions consist of three main structural proteins, peplomer spike (S) protein, transmembrane (M) protein and nucleocapsid (N) protein [16]. FCoV is classified into types I and II according to the amino acid sequence of its S protein and the reactivity to anti-FIPV S monoclonal antibodies (MAb) [9, 14, 15]. FCoV is also classified into 2 biotypes based on differences in pathogenicity: feline enteric coronavirus (FECV) and FIPV. Cats infected with FECV do not develop disease, but FIPV infection induces feline infectious peritonitis (FIP). FIP is a fatal disease, mainly leading to the development of immune complex vasculitis accompanied by necrosis and pyogenic granulomatous inflammation. It has been proposed that FIPV arises from FECV by mutation but the exact mutation and the inducing factors have not yet been clarified [21, 27].

Type II FCoV is known to utilize feline aminopeptidase N (fAPN) as its virus receptor [7]. FIPV targets macrophages, and macrophage infection is enhanced in the presence of antibodies (antibody-dependent enhancement, ADE). ADE activity in FIPV infection is induced when anti-FIPV-S antibody-bound viruses infect macrophages by binding of the Fc region of the antibody to the Fc receptor on the macrophage surface [2, 10, 18]. In addition to FIPV, there have been several reports concerning ADE of other virus infections (dengue virus, human immunodeficiency virus and respiratory syncytial virus, etc.) [4, 5, 20, 22, 23, 25].

We previously reported that when feline macrophages or

human cells of monocyte lineage were inoculated with type II FIPV that had been reacted with the serum of type I or II FIPV-infected cats, ADE was observed only when type II FIPV was reacted with the serum of type II FIPV-infected cats [12]. However, despite the fact that more than 70% of FIP cats have been infected with type I FIPV, it is not clear whether type I FIPV, like type II, induces ADE by re-infection with the same serotype FIPV. Moreover, it is unclear whether ADE is induced by infection with the same serotype virus alone in cats as in the *in-vitro* study.

In this study, we examined whether ADE was induced in cats that had been passively immunized with anti-type I or II FIPV antibodies. Subsequently inoculated with type I FIPV, that is, whether type I FIPV, like type II, induced ADE by re-infection with the same serotype FIPV.

MATERIALS AND METHODS

Cell cultures and viruses: *Felis catus* whole fetus-4 (fcwf-4) cells were cultured in a 1:1 mixture (v/v) of Eagle's minimum essential medium and L-15 medium, supplemented with 5% fetal calf serum (FCS) and antibiotics. Type I FIPV strain KU-2 (type I FIPV KU-2) and type II FIPV strain 79-1146 (type II FIPV 79-1146) were grown in fcwf-4 cells at 37°C. The type I FIPV KU-2 was isolated in our laboratory, and type II FIPV 79-1146 was supplied by Dr. M. C. Horzinek of State University Utrecht, The Netherlands.

Experimental animals: Anti-FCoV antibody-negative twenty-one specific pathogen-free (SPF) cats aged 4–6 months were used. The cats were maintained in a temperature-controlled isolated facility. All experiments were performed in accordance with the Guidelines for Animal Experiments of Kitasato University.

Passive immunization with anti-FIPV antibodies and

*CORRESPONDENCE TO: HOHDATSU, T., Laboratory of Veterinary Infectious Disease, School of Veterinary Medicine, Kitasato University, Towada, Aomori 034-8628, Japan.
e-mail: hohdatsu@vmas.kitasato-u.ac.jp

virus inoculation in SPF cats: Serum from FIPV-seropositive healthy cats and ascites derived from FIP cats were used in the experiment. The sera and ascites were heated at 56°C for 30 min before administration into cats.

Four cats were subcutaneously administered with serum (3 ml or 30 ml) from type I FIPV KU-2-infected cats, and two cats were administered with IgG (3 ml or 30 ml) purified from type I FIPV KU-2-infected cats-derived ascites by ammonium sulfate precipitation. The cats were subcutaneously inoculated with type I FIPV KU-2 ($10^{4.3}$ TCID₅₀/head) 3 days after passive immunization. Five SPF cats inoculated with the virus without passive immunization were regarded as the control group.

Similarly, six cats were subcutaneously administered with serum from type II FIPV 79-1146-infected cats. The cats were subcutaneously inoculated with type I FIPV KU-2 ($10^{4.3}$ TCID₅₀/head) 3 days after passive immunization. As control, 4 cats without passive immunization were inoculated with only the virus.

These cats were checked daily for their clinical signs, and measured their body temperature and weight every 3 days. Serum was collected every 6–7 days for the detection of antibodies against FIPV. FIP diagnosis was confirmed upon postmortem examination, revealing peritoneal or pleural

Enzyme-linked immunosorbent assay (ELISA): The viral antigen used in ELISA was detergent-disrupted, purified type II FIPV 79-1146 virions were appropriately diluted with carbonate buffer (0.05 M, pH 9.6). A hundred μ l of dilutions was pipetted into each well of 96-well flat-bottomed plates. After washing with PBS containing 0.02% Tween-20, each well of the plates was added 100 μ l of the test serum sample. Horseradish peroxidase-conjugated goat anti-cat IgG (ICN Pharmaceuticals, Inc, U.S.A.) were diluted to the optimal concentration with PBS containing 10% FCS and 0.05% Tween-20, 100 μ l of the dilution was added to each well of the plates. After incubation at 37°C for 30 min, each well received 100 μ l of substrate solution and was incubated at 25°C for 20 min in a dark room. The substrate solution was prepared by dissolving o-phenylenediamine dihydrochloride at a concentration of 0.4 mg/ml in 0.1 M citric acid and 0.2 M Na₂HPO₄ buffer (pH 4.8) and adding 0.2 μ l/ml of 30% H₂O₂. The reaction was stopped with 3 N H₂SO₄ solution and the optical density (OD) at 492 nm was determined.

Neutralization test: The test sera were serially 2-fold diluted in medium and mixed with an equal volume of a virus suspension containing approximately 200 TCID₅₀/100 μ l and the mixtures were incubated at 37°C for 60 min. Each mixture was then inoculated into the fcfw-4 cell cultures in 96-well flat-bottomed plates, and incubation was made in an atmosphere of 5% CO₂ in air at 37°C for 3 days. For each serum dilution tests were duplicated. The antibody titer was expressed as a reciprocal of the highest dilution of the test sera that inhibiting cytopathic effect completely.

Statistical analysis: Data were analyzed by the Mann-Whitney test. Differences between comparisons were considered significant a $p < 0.01$.

RESULTS

ADE after type I FIPV infection in cats passively immunized with antiserum against type I FIPV and purified ascitic IgG from type I FIPV: SPF cats were passively immunized with serum or purified ascitic IgG from type I FIPV KU-2-infected cats and inoculated with type I FIPV KU-2. The neutralizing antibody titer against type I FIPV KU-2 was 1:320, the ELISA antibody titer against purified soluble type II FIPV 79-1146 antigen was 1:12600 in both the serum- and purified ascitic IgG-administered cats.

Time-course changes in the serum anti-FIPV antibody level were investigated by ELISA using purified soluble FIPV antigen. In cats passively immunized with 3 ml of antiserum against type I FIPV KU-2 and cat passively immunized with 3 ml of IgG purified from type I FIPV KU-2-infected cat-derived ascites, the ELISA OD value was increased to 0.1–0.2 on the day of virus inoculation (day 3 post passive immunization). In cats without passive immunization (control group), the ELISA OD value continuously increased from day 12 after inoculation with type I FIPV KU-2 (Fig. 1a). In cats immunized with 30 ml of the antiserum and immunized with 30 ml of the purified ascitic IgG, the ELISA OD value was increased to 0.4–0.8, respectively, on the day of virus inoculation (Fig. 1b). A continuous increase in the ELISA OD value from day 12 after inoculation was also noted in cats immunized with antiserum against type I FIPV KU-2 (Fig. 1b). However, the ELISA OD value started to decrease on day 6 after inoculation in Cat Nos. 2F and 0F passively immunized with 30 ml of antiserum against type I FIPV KU-2, and then re-increased from day 18 or 24.

In cats passively immunized with 3 ml of antiserum against type I FIPV KU-2, the neutralizing antibody titer was increased to four fold on the day of virus inoculation (day 3 post passive immunization). In cats immunized with 30 ml of the antiserum, the neutralizing antibody titer was increased to 8 and 16 fold, respectively, on the day of virus inoculation. In cats without passive immunization, the neutralizing antibody titer started to increase on day 6 after inoculation with type I FIPV KU-2, and reached 16–64 fold on day 24 (Fig. 2a). In cat passively immunized with 3 ml of IgG purified from ascites of cats infected with type I FIPV KU-2, the neutralizing antibody titer was increased to four fold on the day of virus inoculation. In cat immunized with 30 ml of the purified ascitic IgG, the titer was increased to eight fold (Fig. 2b). The neutralizing antibody titer also increased after inoculation with type I FIPV KU-2 in cats passively immunized with antiserum against type I FIPV KU-2 (Fig. 2b).

In the control group, FIP developed 69 days after type I FIPV KU-2 inoculation only in Cat No. 9E out of 5 animals. In cats immunized with antiserum against type I FIPV KU-2, Cat Nos. 0F, D3, and 8E developed FIP on day 24, Cat Nos. Q8 and C3 developed FIP on day 30, and Cat No. 2F developed FIP on day 36 after type I FIPV KU-2 inoculation. Figure 3 shows the survival rate of cats immunized

Fig. 1. Anti-FIPV antibody levels after type I FIPV infection in cats passively immunized with serum and purified ascitic IgG from type I FIPV-infected cats: (a) Changes in the ELISA OD value in cats inoculated with type I FIPV without passive immunization (n=5). (b) Changes in the ELISA OD value in cats inoculated with type I FIPV after passive immunization with anti-type I FIPV antiserum or Ig purified from ascites of FIP cats (purified ascitic Ig) (neutralizing antibody titer: 1:320 in both antiserum and ascites) (n=6).

Fig. 2. Anti-type I FIPV neutralizing antibody titers after type I FIPV infection in cats passively immunized with serum and purified ascitic IgG from type I FIPV-infected cats: (a) Changes in the neutralizing antibody titer in cats inoculated with type I FIPV without passive immunization (n=5). (b) Changes in the neutralizing antibody titer in cats inoculated with type I FIPV after passive immunization with anti-type I FIPV antiserum or Ig purified from ascites of FIP cats (purified ascitic Ig) (neutralizing antibody titer: 1:320 in both antiserum and ascites) (n=6).

with antiserum against type I FIPV KU-2 and inoculated with type I FIPV KU-2. The survival rate of cats immunized with antiserum against type I FIPV KU-2 was significantly lower than that of the control group, and the survival time after infection with type I FIPV KU-2 was also shorter.

ADE after type I FIPV infection in cats passively immunized with antiserum against type II FIPV: SPF cats were passively immunized with serum from anti-type II FIPV 79-1146-infected cats and inoculated with type I FIPV KU-2. The neutralizing antibody titer against type II FIPV 79-1146 was 1:6400, the ELISA antibody titer against purified soluble type II FIPV 79-1146 antigen was 1:12600 in the serum administered cats.

Time-course changes in the serum anti-FIPV antibody level were investigated by ELISA using purified soluble FIPV antigen. In cats immunized with 3 ml of antiserum against type II FIPV 79-1146, the ELISA OD value was

increased to 0.1 on the day of virus inoculation (day 3 post passive immunization). In cats without passive immunization (control group), the ELISA OD value continuously increased from day 15 after inoculation with type I FIPV KU-2 (Fig. 4a). In cats immunized with 30 ml of the antiserum against type II FIPV 79-1146, the ELISA OD value was increased to 0.4–0.5 (Fig. 4b). A continuous increase in the ELISA OD value was also noted in cats immunized with antiserum against type II FIPV 79-1146 from day 22 or 29 after inoculation (Fig. 4b). However, the ELISA OD value started to decrease on day 7 after inoculation in cats passively immunized with 30 ml of antiserum against type II FIPV 79-1146, and then re-increased from day 22 or 43, and the ELISA OD value was maintained at about 0.3 from day 29 to 85 after inoculation in Cat No. SV13 immunized with 3 ml of antiserum against type II FIPV 79-1146.

In cats immunized with 3 ml of antiserum against type II

Fig. 3. Survival rates of cats inoculated with type I FIPV after passive immunization with serum and purified ascitic IgG from type I FIPV-infected cats.

Fig. 4. Anti-FIPV antibody levels after type I FIPV infection in cats passively immunized with serum from type II FIPV-infected cats: (a) Changes in the ELISA OD value in cats inoculated with type I FIPV without passive immunization ($n=4$). (b) Changes in the ELISA OD value in cats inoculated with type I FIPV after passive immunization with anti-type II FIPV antiserum (neutralizing antibody titer: 1:6400) ($n=6$).

FIPV 79-1146, the neutralizing antibody titer against type II FIPV 79-1146 was increased to 8 or 16 fold on the day of virus inoculation (day 3 post passive immunization). In cats immunized with 30 ml of the antiserum against type II FIPV 79-1146, the neutralizing antibody titer against type II FIPV 79-1146 was increased to 128 fold (Fig. 5d). However, the neutralizing antibody titer against type I FIPV KU-2 did not increase in response to type I FIPV KU-2 inoculation in any cat immunized with antiserum against type II FIPV 79-1146 (Fig. 5c).

The neutralizing antibody titer against type I FIPV KU-2 was increased in response to type I FIPV KU-2 inoculation in control cats without immunization (control group) (Fig. 5a). The neutralizing antibody titer against type I FIPV KU-2 was also increased in response to type I FIPV KU-2 inoculation in cats immunized with antiserum against type II

FIPV 79-1146 (Fig. 5c). In contrast, no increase in the neutralizing antibody titer against type II FIPV 79-1146 in response to type I FIPV KU-2 inoculation was noted in the control group (Fig. 5b). In the group passively immunized with antiserum against type II FIPV 79-1146, the neutralizing antibody titer against type II FIPV 79-1146 decreased over time. In groups of 3 cats treated with 3 and 30 ml of antiserum against type II FIPV 79-1146, the neutralizing antibody titer against type II FIPV 79-1146 decreased to a level lower than the detection limit (lower than two) on days 28 and 77 after type I FIPV KU-2 inoculation, respectively, corresponding to the initial antibody titer passively administered (Fig. 5d).

In cats immunized with antiserum against type II FIPV 79-1146, FIP developed on day 56 after type I FIPV KU-2 inoculation only in Cat No. SV63 out of 6 cats, but no cat

Fig. 5. Neutralizing antibody titers against types I and II FIPV after type I FIPV infection in cats passively immunized with serum from type II FIPV-infected cats: 1) Changes in neutralizing antibody titers against type I FIPV (a) and type II FIPV (b) after type I FIPV infection in cats without passive immunization ($n=4$). 2) Changes in neutralizing antibody titers against type I FIPV (c) and type II FIPV (d) after type I FIPV infection in cats passively immunized with anti-type II FIPV antiserum (neutralizing antibody titer: 1:6400) ($n=6$).

Fig. 6. Survival rate of cats passively immunized with anti-type II FIPV antiserum and inoculated with type I FIPV: N.S. indicates not significant.

developed FIP in the control group. Figure 6 shows the survival rate of cats passively immunized with serum from type II FIPV 79-1146-infected cats and inoculated with type I FIPV KU-2. No significant difference was noted in the survival rate between cats immunized with antiserum against

type II FIPV 79-1146 and control groups.

DISCUSSION

The antibody titer, including the neutralizing antibody

titer, increases in FIPV infection, as in most virus infections. However, anti-FCoV antibodies are not effective for elimination of the virus, and, inversely, they enhance FIP development in the laboratory experiment [19]. Analysis using anti-FIPV MAb revealed that epitopes involved in ADE exist mainly on the S protein. Antibodies which neutralized virus propagated in Fc receptor-negative cells, such as the feline kidney cell line CrFK, induced strong ADE activity in Fc receptor-positive feline macrophages infected with FIPV, suggesting a close association between the neutralizing and infection-enhancing epitopes [2, 11, 17, 18].

There are two serotypes of FIPV, types I and II [9, 14, 15]. Four different serotypes of dengue virus exist, to which antibodies induce ADE, as with FIPV. The host infected with other serotypes of dengue virus develops high-mortality dengue hemorrhagic fever associated with ADE [3, 6]. In FIPV infection, unlike in dengue virus infection, ADE was observed in cats that had been passively immunized with anti-type I FIPV antibodies and subsequently infected with the same serotype (I) of FIPV, but not with the different type (II) of FIPV. These results support the *in vitro* experimental results that ADE was observed when cat macrophages or human cells of monocyte lineage were inoculated with type II FIPV that had been reacted with the serum of type II FIPV-infected cats [12].

We investigated ADE of infection of feline alveolar macrophages with FIPV KU-2, FIPV UCD-1 and FIPV Black strain, which are type I FIPV [12]. These viruses did not multiply in cultured feline alveolar macrophages, and enhancement of the infection by antibodies was not observed. However, in this study, in cats passively immunized with the serum of type I FIPV-infected cats, ADE was observed after inoculation with type I FIPV. Since Van Hamme *et al.* [26] have suggested that monocytes may be the target of type I FIPV, we need to investigate whether the occurrence of ADE of type I FIPV infection can be reproduced *in vitro* using monocytes instead of feline alveolar macrophages. We intend to prepare monoclonal antibodies reacting with type I FIPV S protein to evaluate the development of ADE of type I FIPV infection in detail.

The neutralizing antibody titer of the type II FIPV-infected cat serum used in this study was approximately 10 times higher than that of type I FIPV-infected cat serum or IgG purified from ascitic fluid. It is known that the neutralizing antibody titer in the serum of type I FIPV-infected cats against type I FIPV is lower than that of type II FIPV-infected cats against type II FIPV. The ELISA antibody titers of serum and IgG purified from ascetic fluid against purified soluble FIPV antigen were similar. Probably, a similar level of anti-FIPV antibodies was contained, although the neutralizing antibody titers against the specific viruses were different. The cats passively immunized with type II FIPV-infected cat serum had a high neutralizing antibody titer to the homologous virus, whereas those passively immunized with type I FIPV-infected cat serum had a high ELISA OD value. Based on these facts, groups of cats were passively immunized with 3 or 30 ml of FIPV-infected cat

serum for the intergroup comparison of responses after inoculation with type I FIPV. Cats immunized with 30 ml of type I FIPV-infected cat serum or ascitic IgG and those immunized with 3 ml of type II FIPV-infected cat serum had a similar neutralizing antibody titer on day 3 after passive immunization (on the day of virus inoculation). All 3 cats immunized with 30 ml of type I FIPV-infected cat serum or ascitic IgG developed FIP after type I FIPV inoculation, whereas the cats immunized with 3 ml of type II FIPV-infected cat serum did not. These results indicate that, when cat serum contained antibodies with a similar neutralizing titer, ADE of type I FIPV infection occurred in the anti-type I FIPV-immunized cats alone.

The possibility cannot be excluded that the FIPV antigen and heat-stable substances other than anti-type I FIPV antibodies were present in FIPV-infected cat serum and FIP cat-derived ascitic IgG, thereby being involved in ADE induction. However, if substances in the serum other than anti-type I FIPV antibodies had been involved in ADE induction, ADE would also have occurred in cats passively immunized with type II FIPV-infected cat serum, which was not the case in this study. In addition, in cats passively immunized with type II FIPV-infected cat serum, the neutralizing antibody titer rose temporarily after immunization, and then gradually decreased. In other words, even if the type II FIPV antigen was present in the serum, it was not at a level sufficient to induce antibody production, probably not affecting the present experimental system. Thus, we consider that mainly anti-type I FIPV antibodies induced ADE in this study.

It was also confirmed that the probability of developing FIP increased when anti-type I FIPV antibody-positive cats were infected with type I FIPV. Many domestic cats possess anti-type I FCoV antibodies, and numerous field cases of FIP are caused by type I FIPV infection [8, 13], suggesting that FIPV re-infection induces ADE and advances FIP development in domestic cats. However, Addie *et al.* [1] reported that FCoV re-infection of anti-FCoV antibody-positive domestic cats might not result in the development of ADE. Although the details are unclear, differences in the immunological condition of FCoV-infected cats may be the reason why the phenomenon noted in this experiment does not occur in domestic cats. It is assumed that ADE does not occur in cats which have acquired strong cellular immunity, even if they possess anti-FCoV antibodies, escaping from FIP development. It may also be possible that anti-FCoV antibodies prevent FIPV infection, avoiding ADE, when the anti-FCoV neutralizing antibody titer is high. We previously reported that FIPV infection of macrophages was completely neutralized at a high MAb concentration, but dilution of the antibodies inversely induced ADE in an *in vitro* study [10].

We demonstrated that ADE was induced by re-infection with the identical serotype virus in FIPV infection, unlike dengue virus infection. We have recently reported that TNF-alpha released from macrophages showing ADE of FIPV infection is closely involved in the progression of the

pathological state of FIP [24]. The ADE of FIPV infection is a barrier to the development of FIPV vaccines. Moreover, it is possible to study ADE of FIPV infection using cultured cells (*in vitro*) or experimental infection of cats (*in vivo*), thereby comparing responses in cultured cells and the host. Thus, the study of ADE of FIPV infection provides an appropriate animal model for the understanding of human infection with deadly viruses associated with ADE, such as dengue virus and ebola virus infection. It seems very important to conduct studies on the occurrence of ADE of FIPV infection.

ACKNOWLEDGEMENT. This work was supported in part by Ministry of Health, Labor, and Welfare (grant H16-Shinkoh-9) and The Waksman foundation of Japan Inc. (grant 07-9).

REFERENCES

- Addie, D.D., Toth, S., Murray, G.D. and Jarrett, O. 1995. Risk of feline infectious peritonitis in cats naturally infected with feline coronavirus. *Am. J. Vet. Res.* **56**: 429–434.
- Corapi, W.V., Olsen, C.W. and Scott, F.W. 1992. Monoclonal antibody analysis of neutralization and antibody-dependent enhancement of feline infectious peritonitis virus. *J. Virol.* **66**: 6695–6705.
- Halstead, S.B. 1970. Observations related to pathogenesis of dengue hemorrhagic fever. VI. Hypothesis and discussion. *Yale J. Biol. Med.* **42**: 350–363.
- Halstead, S.B. 2003. Neutralization and antibody-dependent enhancement of dengue viruses. *Adv. Virus. Res.* **60**: 421–467.
- Halstead, S.B., Lan, N.T., Myint, T.T., Shwe, T.N., Nisalak, A., Kalyanarooj, S., Nimmannitya, S., Soegijanto, S., Vaughn, D.W. and Endy, T.P. 2002. Dengue hemorrhagic fever in infants: research opportunities ignored. *Emerg. Infect. Dis.* **12**: 1474–1479.
- Halstead, S.B., Shotwell, H. and Casals, J. 1973. Studies on the pathogenesis of dengue infection in monkeys. II. Clinical laboratory responses to heterologous infection. *J. Infect. Dis.* **128**: 15–22.
- Hohdatsu, T., Izumiya, Y., Yokoyama, Y., Kida, K. and Koyama, H. 1998. Differences in virus receptor for type I and type II feline infectious peritonitis virus. *Arch. Virol.* **143**: 839–550.
- Hohdatsu, T., Nakamura, M., Ishizuka, Y., Yamada, H. and Koyama, H. 1991. A study on the mechanism of antibody-dependent enhancement of feline infectious peritonitis virus infection in feline macrophages by monoclonal antibodies. *Arch. Virol.* **120**: 207–217.
- Hohdatsu, T., Okada, S., Ishizuka, Y., Yamada, H. and Koyama, H. 1992. The prevalence of types I and II feline coronavirus infections in cats. *J. Vet. Med. Sci.* **54**: 557–562.
- Hohdatsu, T., Okada, S. and Koyama, H. 1991. Characterization of monoclonal antibodies against feline infectious peritonitis virus type II and antigenic relationship between feline, porcine, and canine coronaviruses. *Arch. Virol.* **117**: 85–95.
- Hohdatsu, T., Yamada, H., Ishizuka, Y. and Koyama, H. 1993. Enhancement and neutralization of feline infectious peritonitis virus infection in feline macrophages by neutralizing monoclonal antibodies recognizing different epitopes. *Microbiol. Immunol.* **37**: 499–504.
- Hohdatsu, T., Yamada, M., Tominaga, R., Makino, K., Kida, K. and Koyama, H. 1998. Antibody-dependent enhancement of feline infectious peritonitis virus infection in feline alveolar macrophages and human monocyte cell line U937 by serum of cats experimentally or naturally infected with feline coronavirus. *J. Vet. Med. Sci.* **60**: 49–55.
- Kummrow, M., Meli, M.L., Haessig, M., Goenczi, E., Poland, A., Pedersen, N.C., Hofmann-Lehmann, R. and Lutz, H. 2005. Feline coronavirus serotypes 1 and 2: seroprevalence and association with disease in Switzerland. *Clin. Diagn. Lab. Immunol.* **12**: 1209–1215.
- Motokawa, K., Hohdatsu, T., Aizawa, C., Koyama, H. and Hashimoto, H. 1995. Molecular cloning and sequence determination of the peplomer protein gene of feline infectious peritonitis virus type I. *Arch. Virol.* **140**: 469–480.
- Motokawa, K., Hohdatsu, T., Hashimoto, H. and Koyama, H. 1996. Comparison of the amino acid sequence and phylogenetic analysis of the peplomer, integral membrane and nucleocapsid proteins of feline, canine and porcine coronaviruses. *Microbiol. Immunol.* **40**: 425–433.
- Olsen, C.W. 1993. A review of feline infectious peritonitis virus: molecular biology, immunopathogenesis, clinical aspects, and vaccination. *Vet. Microbiol.* **36**: 1–37.
- Olsen, C.W., Corapi, W.V., Jacobson, R.H., Simkins, R.A., Saif, L.J. and Scott, F.W. 1993. Identification of antigenic sites mediating antibody-dependent enhancement of feline infectious peritonitis virus infectivity. *J. Gen. Virol.* **74**: 745–749.
- Olsen, C.W., Corapi, W.V., Ngichabe, C.K., Baines, J.D. and Scott, F.W. 1992. Monoclonal antibodies to the spike protein of feline infectious peritonitis virus mediate antibody-dependent enhancement of infection of feline macrophages. *J. Virol.* **66**: 956–965.
- Pedersen, N.C. and Boyle, J.F. 1980. Immunologic phenomena in the effusive form of feline infectious peritonitis. *Am. J. Vet. Res.* **41**: 868–876.
- Polack, F.P., Hoffman, S.J., Crujeiras, J. and Griffin, D.E. 2003. A role for nonprotective complement-fixing antibodies with low avidity for measles virus in atypical measles. *Nat. Med.* **9**: 1209–1213.
- Poland, A.M., Vennema, H., Foley, J.E. and Pedersen, N.C. 1996. Two related strains of feline infectious peritonitis virus isolated from immunocompromised cats infected with a feline enteric coronavirus. *J. Clin. Microbiol.* **34**: 3180–3184.
- Sullivan, N.J. 2001. Antibody-mediated enhancement of viral disease. *Curr. Top. Microbiol. Immunol.* **260**: 145–169.
- Takada, A., Kawaoka, Y. 2003. Antibody-dependent enhancement of viral infection: molecular mechanisms and in vivo implications. *Rev. Med. Virol.* **13**: 387–398.
- Takano, T., Hohdatsu, T., Toda, A., Tanabe, M. and Koyama, H. 2007. TNF-alpha, produced by feline infectious peritonitis virus (FIPV)-induced macrophages, upregulates expression of type II FIPV receptor feline aminopeptidase N in feline macrophages. *Virology* **364**: 64–72.
- Tirado, S.M. and Yoon, K.J. 2003. Antibody-dependent enhancement of virus infection and disease. *Viral. Immunol.* **16**: 69–86.
- Van Hamme, E., Dewerchin, H.L., Cornelissen, E. and Nauwynck, H.J. 2007. Attachment and internalization of feline infectious peritonitis virus in feline blood monocytes and Crandell feline kidney cells. *J. Gen. Virol.* **88**: 2527–2532.
- Vennema, H., Poland, A., Foley, J. and Pedersen, N.C. 1998. Feline infectious peritonitis viruses arise by mutation from endemic feline enteric coronaviruses. *Virology* **243**: 150–157.