

LETTERS

To test the efficacy of pegylated IFN- α as an antiviral agent postexposure, we injected pegylated IFN- α intramuscularly into a postexposure group of four macaques, 1 and 3 d after experimental SCV infection, and evaluated them in the same way as the prophylactic group. Excretion of SCV from the pharynx was found only 2 d.p.i., at a significantly ($P < 0.05$) reduced level compared with the control group (Fig. 3). Moreover, the virus titer in the lungs at 4 d.p.i. was significantly ($P < 0.01$) decreased, whereas the remaining parameters were less reduced (Fig. 4a–c). These results show that use of pegylated IFN- α 1 d postexposure protects type 1 pneumocytes of experimentally infected macaques from SCV infection, but is less effective than prophylactic use.

In this study, we have shown that type 1 pneumocytes are the main target cells for SCV infection of cynomolgus macaques early in the disease, and that pegylated IFN- α protects type 1 pneumocytes from SCV infection. The first point—type 1 pneumocytes as the primary target cell—is evident from the extensive presence of SCV in type 1 pneumocytes at 4 d.p.i. (Fig. 1c,d). Targeting of type 1 pneumocytes by SCV explains why clinical disease and lesions are centered on the lower respiratory tract^{7,11,23}, and fits with the lesions in early fatal SARS cases in humans^{11,23} and in experimentally infected macaques euthanized at 6 d.p.i. (ref. 2). When the pathological studies in humans and macaques are examined together, the following temporal sequence of lung lesions emerges: viral infection and subsequent loss of type 1 pneumocytes; acute DAD characterized by flooding of alveolar lumina with highly proteinaceous edema fluid; chronic DAD characterized by type 2 pneumocyte hyperplasia; and, in severe cases, extensive pulmonary fibrosis. This sequence of events corresponds to the stereotypic alveolar reaction to acute lung injury from a variety of causes¹². More detailed experimental studies will be needed to identify other possible target cells and further elucidate the pathogenesis of SARS.

The second point—that pegylated IFN- α protects type 1 pneumocytes from SCV infection—is based on the beneficial effect of pegylated IFN- α therapy initiated 3 d before SCV inoculation of macaques. In these macaques, SCV infection of type 1 pneumocytes and severity of lung lesions were significantly reduced (Fig. 4), and viral excretion was abrogated (Fig. 3). Pegylated IFN- α treatment may have an important influence on the outcome of SARS. In both virus-induced^{14,15} and toxin-induced²⁴ DAD, the severity of pulmonary damage is dose dependent, with higher doses causing increased pulmonary fibrosis, loss of lung function and mortality. Reduction of the viral load by pegylated IFN- α therapy at an early stage of SCV infection might therefore help prevent serious or fatal outcome of SARS

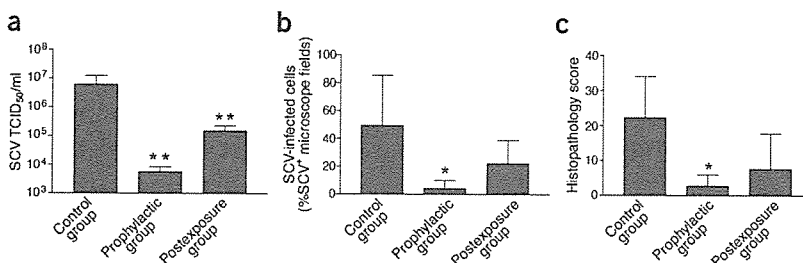


Figure 4 Effect of pegylated IFN- α on SCV replication, viral antigen expression and histological lesions in lungs of SCV-infected macaques at 4 d.p.i. (a) SCV titration of lung homogenates. TCID₅₀, median tissue culture infectious dose. (b) Immunohistochemical detection of SCV-infected cells in lung sections. (c) Histopathological scoring of lung sections. SCV-infected macaques were treated with pegylated IFN- α prophylactically ($n = 4$) or postexposure ($n = 4$), or with PBS (control group; $n = 4$). Data are expressed as mean \pm s.d. *, $P < 0.05$; **, $P < 0.01$ compared with control group.

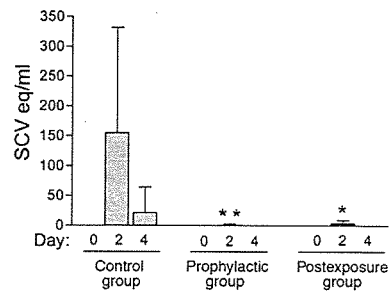


Figure 3 Effect of pegylated IFN- α on SCV excretion in macaques. SCV detection in pharyngeal swabs taken at 0, 2 or 4 d.p.i. from macaques treated with PBS (control group; $n = 4$) or pegylated IFN- α prophylactically ($n = 6$) or postexposure ($n = 4$). Eq, equivalents. Data are expressed as mean \pm s.d. *, $P < 0.05$; **, $P < 0.01$ compared with control group at 2 d.p.i.

associated with pulmonary fibrosis. In addition to potential disease mitigation, reduced viral excretion through pegylated IFN- α therapy may also have an epidemiological effect by reducing the spread of SCV in the human population. Whether the mechanism of pegylated IFN- α protection is by direct antiviral activity or immunostimulatory effects²⁵ remains to be determined.

The reduced protection of type 1 pneumocytes by pegylated IFN- α in the postexposure group compared with the prophylactic group was probably because the initiation of therapy (at 1 d.p.i.) was too close to the peak of viral infection in the lungs (at 2 d.p.i.; Fig. 3). Thus, substantial infection of type 1 pneumocytes may already have occurred by the time pegylated IFN- α reached therapeutic levels. These *in vivo* findings are in accordance with the reduced *in vitro* activity against SCV of IFN- α added after infection, compared with IFN- α added before infection²⁰. It also corresponds to the results of IFN therapy against acute virus infections in most animal models, where IFN is most effective when administered before virus inoculation or before the peak of virus replication in the target organ²⁶.

The time interval during which effective postexposure treatment with pegylated IFN- α can be initiated may be longer in humans than in experimentally infected macaques. This is because the peak of SCV infection in the lungs occurs around 16 d.p.i. in humans—based on an average incubation period of 6 d (refs. 9,27) and a peak in viral excretion 10 d after onset of symptoms²⁸—compared with 2 d.p.i. in the macaques (Fig. 3).

In conclusion, these studies show that type 1 pneumocytes are the main target cells for SCV infection of macaques early in the disease, and that pegylated IFN- α , a commercially available antiviral drug, protects these cells from SCV infection. We believe that these preliminary results warrant clinical studies with pegylated IFN- α , if and when SARS re-emerges. Prophylactic or early postexposure treatment with pegylated IFN- α may help reduce the impact of SCV infection on health-care workers and others possibly exposed to SCV, and may limit the spread of the virus in the human population.

METHODS

Antiviral assay. Wells containing Vero cells were treated in triplicate with pegylated recombinant IFN- α (PEG-Intron, Schering) for 16 h and infected

with 100 median tissue culture infectious dose (TCID₅₀)/well SCV (obtained from patient 5688, who died of SARS²). After 16 h, the supernatant was removed and cells were fixed with 10% neutral-buffered formalin and 70% ethanol (10 min at room temperature). SCV antigen-positive cells were visualized by immunohistochemistry, as described below. The numbers of SCV-infected cells per well were summarized as mean \pm s.d.

Macaque studies. Approval for animal experiments was obtained from the Institutional Animal Welfare Committee. Three groups of cynomolgus macaques were infected intratracheally with 1×10^6 TCID₅₀ SCV suspended in 5 ml of PBS. The control group ($n = 4$) was injected intramuscularly with PBS, while the prophylactic ($n = 6$) and postexposure ($n = 4$) groups were treated with pegylated IFN- α at a dose of 3 mg/kg. The prophylactic group was injected with pegylated IFN- α on days -3, -1, 1 and 3 after SCV infection; the postexposure group was injected on days 1 and 3 after SCV infection. Four macaques from each group were euthanized on day 4 after infection. At days -3, -2, -1, 0, +2 and +4, we anesthetized the macaques with ketamine, collected 10 ml blood from inguinal veins and took pharyngeal swabs, which were placed in 1 ml transport medium²⁹. Pharyngeal swabs were frozen at -70 °C until RT-PCR analysis. Pegylated IFN- α levels were determined using ELISA (Bender MedSystems Diagnostics) with PEG-Intron as a standard. Neopterin levels were determined as described²². Necropsies were done according to a standard protocol; one lung of each monkey was inflated with 10% neutral-buffered formalin by intrabronchial intubation and suspended in 10% neutral-buffered formalin overnight. Samples were collected in a standard manner (one from the cranial part of the lung, one from the medial part and two from the caudal part), embedded in paraffin, cut at 5 μ m and used for immunohistochemistry (see below) or stained with H&E.

For semiquantitative assessment of SCV infection-associated inflammation in the lung, each H&E-stained section was examined for inflammatory foci by light microscopy using a 10 \times objective. Each focus was scored for size (1, smaller than or equal to area of 10 \times objective; 2, larger than area of 10 \times objective and smaller than or equal to area of 2.5 \times objective; 3, larger than area of 2.5 \times objective) and severity of inflammation (1, mild; 2, moderate; 3, marked). The cumulative scores for the inflammatory foci provided the total score per animal. Sections were examined without knowledge of the identity of the macaques. The lung sections of one monkey in the postexposure group were not assessed because of the presence of inflammation from pre-mortem aspiration of food remains. Lung samples from a control macaque were used for transmission electron microscopy as described².

Three lung tissue samples taken from the other lung (one from the cranial part of the lung, one from the medial part and one from the caudal part) were homogenized in 2 ml transport medium²⁹ using Polytron PT2100 tissue grinders (Kinematica). After low-speed centrifugation, the homogenates were frozen at -70 °C until inoculation on Vero 118 cell cultures in tenfold serial dilutions. The identity of the isolated virus was confirmed as SCV by RT-PCR of the supernatant.

Immunohistochemistry. The same formalin-fixed, paraffin-embedded lung samples that were used for histology—one from the cranial part of the lung, one from the medial part and two from the caudal part—were cut at 5 μ m and stained for SCV antigen using either biotinylated purified human IgG from a convalescent SARS patient, negative-control biotinylated purified human IgG, or the dilution buffer, as described previously². Twenty-five arbitrarily chosen 20 \times objective fields of lung parenchyma in each lung section were examined by light microscopy for the presence of SCV antigen expression, without knowledge of the identity of the macaques. The cumulative scores for each animal were expressed as number of positive fields per 100 fields (%). Selected lung sections from macaques in the control group were stained with monoclonal antibody AE1/AE3 to cytokeratin (Neomarkers) for identification of epithelial cells, according to standard immunohistochemical procedures.

SCV RT-PCR. RT-PCR with primers and probe specific for the nucleoprotein gene of SCV was used to quantify SCV in swabs, as described². Serial dilutions of the SCV stock were used as a standard, and results were expressed as SCV equivalents per ml swab medium.

Statistical analysis. Data were compared using the Student *t*-test (antiviral activity of pegylated IFN- α against SCV *in vitro* and its biological activity in macaques) or one-way ANOVA and Dunnett's multiple-comparison test (effect of pegylated

IFN- α on SCV excretion, SCV replication, viral antigen expression and histological lesions in the lungs). Differences were considered significant at $P < 0.05$.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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- Fouchier, R.A.M. *et al.* Koch's postulates fulfilled for SARS virus. *Nature* **423**, 240 (2003).
- Kuiken, T. *et al.* Newly discovered coronavirus as the primary cause of severe acute respiratory syndrome. *Lancet* **362**, 263–270 (2003).
- Marra, M.A. *et al.* The genome sequence of the SARS-associated coronavirus. *Science* **300**, 1399–1404 (2003).
- Rota, P.A. *et al.* Characterization of a novel coronavirus associated with severe acute respiratory syndrome. *Science* **300**, 1394–1399 (2003).
- Drosten, C. *et al.* Identification of a novel coronavirus in patients with severe acute respiratory syndrome. *N. Engl. J. Med.* **348**, 1967–1976 (2003).
- Ksiazek, T.G. *et al.* A novel coronavirus associated with severe acute respiratory syndrome. *N. Engl. J. Med.* **348**, 1953–1966 (2003).
- Peiris, J.S.M. *et al.* Coronavirus as a possible cause of severe acute respiratory syndrome. *Lancet* **361**, 1319–1325 (2003).
- Tsang, K.W. *et al.* A cluster of cases of severe acute respiratory syndrome in Hong Kong. *N. Engl. J. Med.* **348**, 1977–1985 (2003).
- Lee, N. *et al.* A major outbreak of severe acute respiratory syndrome in Hong Kong. *N. Engl. J. Med.* **348**, 1986–1994 (2003).
- Poutanen, S.M. *et al.* Identification of severe acute respiratory syndrome in Canada. *N. Engl. J. Med.* **348**, 1995–2005 (2003).
- Nicholls, J.M. *et al.* Lung pathology of fatal severe acute respiratory syndrome. *Lancet* **361**, 1773–1178 (2003).
- Ware, L.B. & Matthay, M.A. The acute respiratory distress syndrome. *N. Engl. J. Med.* **342**, 1334–1349 (2000).
- Williams, M.C. The alveolar epithelium: structure and study by immunohistochemistry. in *Electron Microscopy of the Lung* (ed. Schraufnagel, D.E.) 121–147 (Marcel Dekker, New York, 1990).
- Bellum, S.C. *et al.* Respiratory reovirus 1/L induction of intraluminal fibrosis. A model for the study of bronchiolitis obliterans organizing pneumonia. *Am. J. Pathol.* **150**, 2243–2254 (1997).
- London, L. *et al.* Respiratory reovirus 1/L induction of diffuse alveolar damage: pulmonary fibrosis is not modulated by corticosteroids in acute respiratory distress syndrome in mice. *Clin. Immunol.* **103**, 284–295 (2002).
- Pei, J., Sekelick, M.J., Marcus, P.I., Choi, I.S. & Collisson, E.W. Chicken interferon type 1 inhibits infectious bronchitis virus replication and associated respiratory illness. *J. Interferon Cytokine Res.* **21**, 1071–1077 (2001).
- Smith, A.L., Barthold, S.W. & Beck, D.S. Intranasally administered α/β interferon prevents extension of mouse hepatitis virus, strain JHM, into the brains of BALB/cByJ mice. *Ant. Res.* **8**, 239–245 (1987).
- Turner, R.B., Felton, A., Kosak, K., Kelsey, D.K. & Meschievitz, C.K. Prevention of experimental coronavirus colds with intranasal α -2b interferon. *J. Infect. Dis.* **154**, 443–447 (1986).
- Manns, M.P. *et al.* Peginterferon α -2b plus ribavirin compared with interferon α -2b plus ribavirin for initial treatment of chronic hepatitis C: a randomised trial. *Lancet* **358**, 958–965 (2001).
- Cinatl, J. *et al.* Treatment of SARS with human interferons. *Lancet* **362**, 293–294 (2003).
- Bukowski, R.M. *et al.* Treating cancer with PEG Intron: pharmacokinetic profile and dosing guidelines for an improved interferon- α 2b formulation. *Cancer* **95**, 389–396 (2002).
- Van Gool, A.R. *et al.* Serum amino acids, biopterin and neopterin during long-term immunotherapy with interferon- α in high-risk melanoma patients. *Psychiatry Res.* **119**, 125–132 (2003).
- Franks, T.J. *et al.* Lung pathology of severe acute respiratory syndrome (SARS): a study of 8 autopsy cases from Singapore. *Hum. Pathol.* **34**, 743–748 (2003).
- Bedrossian, C.W., Sussman, J., Conklin, R.H. & Kahan, B. Azathioprine-associated interstitial pneumonitis. *Am. J. Clin. Path.* **82**, 148–154 (1984).
- Biron, C.A. Interferons α and β as immune regulators: a new look. *Immunity* **14**, 661–664 (2001).
- Finter, N.B. & Oldham, R.K. (eds.) Interferons: *In Vivo* and Clinical Studies. Vol. 4 (Elsevier, Amsterdam, 1985).
- Booth, C.M. *et al.* Clinical features and short-term outcomes of 144 patients with SARS in the greater Toronto area. *JAMA* **289**, 2801–2809 (2003).
- Peiris, J.S.M. *et al.* Clinical progression and viral load in a community outbreak of coronavirus-associated SARS pneumonia: a prospective study. *Lancet* **361**, 1767–1772 (2003).
- Fouchier, R.A. *et al.* Detection of influenza viruses from different species by PCR amplification of conserved sequences in the matrix gene. *J. Clin. Microbiol.* **38**, 4096–5001 (2000).

