別紙　5

研究成果の刊行に関する一覧表

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Original article

Construction and in vitro characterization of a chimeric simian and human immunodeficiency virus with the RANTES gene

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Abstract

Chimeric simian–human immunodeficiency virus (SHIV) containing the *env* gene of HIV-1 infects macaque monkeys and provides basic information that is useful for the development of HIV-1 vaccines. Regulated-on-activation-normal-T-cell-expressed-and-secreted (RANTES), a CC-chemokine, enhances antigen-specific T helper type-1 responses against HIV-1. With the final goal of testing the adjuvant effects of RANTES in SHIV-macaque models, we constructed a SHIV having the RANTES gene (SHIV-RANTES) and characterized its properties in vitro. SHIV-RANTES replicated both in human and monkey T cell lines. Along with SHIV-RANTES replication, RANTES was detected in the supernatant of human and monkey cell cultures, at maximal levels of 98.5 and 4.1 ng/ml, respectively. A flow cytometric analysis showed that the expressed RANTES down-modulated CC-chemokine receptor 5 (CCR5) on PM1 cells, which was restored by adding anti-RANTES antibody. UV-irradiated culture supernatants from the SHIV-RANTES-infected cells suppressed replication of CCR5-tropic HIV-1 BaL in PM-1 cells. Differentiating real-time RT-PCR showed that pre-infection of SHIV-RANTES in C8166 cells expressing CCR5 suppressed the replication of HIV-1 BaL. Biological activity of the expressed RANTES and the inserted RANTES gene in SHIV-RANTES remained stable after 10 passages. These results suggest that SHIV-RANTES is worth testing in macaque models.

Keywords: SHIV; RANTES; HIV-1; AIDS

1. Introduction

A successful HIV-1 vaccine is needed to control the worldwide AIDS epidemic. Chimeric simian and human immunodeficiency virus (SHIV) clones containing the HIV-1 *env* genes on a simian immunodeficiency virus (SIV) provide useful information on HIV-1 vaccine development, because SHIVs are readily infectious to macaque monkeys, and show induction of immune responses to HIV-1 Env. We previously reported the in vivo properties of the SHIV-NM3rN (derived from HIV-1 NL432 and SIV mac239) with deletion in the *vpx*, *vpr*, and/or *nef* genes [1]. Macaque monkeys inoculated with these gene-deleted SHIVs induced anti-HIV-1 Env humoral and cell-mediated immunity without causing an AIDS-like disease [1]. Moreover, the monkeys immunized with the *nef*-deleted SHIVs (SHIV-NI), were protected from a challenge with a heterologous pathogenic SHIV [2,3]. Live-attenuated SIV/SHIVs have been shown to be effective vaccines in macaque models. However, serious questions about the pathogenic potential of live-attenuated SIVs [4,5] have dampened enthusiasm for their use in clinical trials. Nevertheless, clarification of the protective mechanisms of attenuated SIV/SHIVs in macaque models could help to improve other vaccine candidates such as live vector-based vaccines and plasmid-DNA immunogens. In general, the immunogenicity of live-attenuated vaccines tends to increase with increasing virulence [6]. Therefore, in attenuating a live virus, there is a trade-off between safety and immunogenicity. A good way to overcome this problem is to genetically engi-

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neer a virus to co-express an immunostimulatory agent such as a cytokine adjuvant. Several studies have demonstrated that insertion of a cytokine in a gene-deleted live-attenuated SIV could boost its immunogenicity and enhance its protection ability [7,8]. This would make it possible to obtain a higher level of immunogenicity from safer, less virulent strains.

Chemokines constitute a family of small proinflammatory cytokines that regulate the activation and migration of leukocytes. Regulated-on-activation-normal-T-cell-expressed-and-secreted (RANTES) is a CC-chemokine and a natural ligand for the CC-chemokine receptors 1 (CCR1), CCR3, and CCR5. Receptors of RANTES are expressed on a variety of cells predominantly associated with T helper type-1 (Th1) responses [9]. An immune response polarized toward a more Th1 response is associated with a reduced viral load and non-progression of disease in HIV-1 infection. RANTES has been found to enhance cellular immune responses resulting in a more effective immune-modulating effect against HIV-1-related virus in rodent and monkey models [10–13]. In addition, infection of macaques with a live-attenuated SIV induced the production of CC-chemokines [14–16], and the up-regulation of CC-chemokines was found to be associated with the sterilizing immunity generated by the vaccine [14]. Moreover, RANTES has been shown to directly inhibit HIV-1 replication in vitro [17,18]. RANTES blocks or down-modulates CCR5 in vitro, which leads to suppression of CCR5-tropic (R5-tropic) HIV-1 infections. These results make RANTES an attractive candidate as a cytokine adjuvant.

To study the adjuvant effect of RANTES against HIV-1 related-virus infections in the macaque model, we have genetically engineered a SHIV to express the human RANTES gene (SHIV-RANTES). In this study, we compare the in vitro properties of SHIV-RANTES with those of its parental SHIV-NI. SHIV-RANTES replicates in both human and monkey cells, and expresses a high amount of RANTES. The RANTES produced with SHIV-RANTES was biologically active as shown by its ability to down-modulate expression of CCR5 and to inhibit the R5-tropic HIV-1 BaL infection. Pre-inoculating cells with SHIV-RANTES more efficiently suppressed a challenge with R5-tropic HIV-1 BaL in vitro than did pre-inoculation with the parental SHIV-NI. These results suggest that SHIV-RANTES will be useful for understanding the effect of RANTES against HIV-1-related infections. These data are an initial step toward the assessment of SHIV-RANTES in vivo.

2. Materials and methods

2.1. Construction of SHIV-RANTES

The SHIV-*nef* vector, designated as SHIV-NI, was constructed from an infectious molecular clone of SHIV-NM3rN [19]. The *env* gene of the SHIV-NM3rN was derived from CXCR4-tropic (X4-tropic) HIV-1 NL432, whose replication

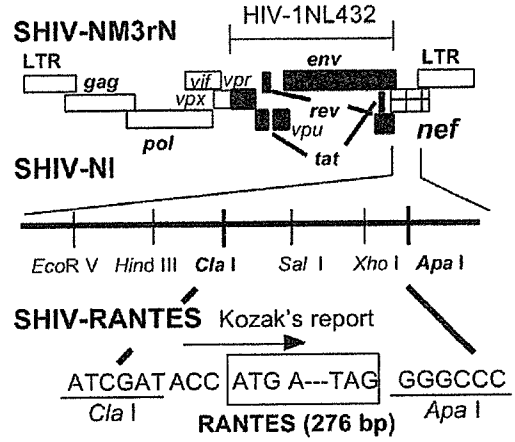

Fig. 1. Genetic structure of SHTV-RANTES. The *Cla* I and *Xho* I region of parental SHIV-NI, the *nef* cassette vector, was replaced by the human RANTES gene. The ORF including the initiation (ATG) and stop (TAG) codons of the RANTES gene is shown in the box. The flanking sequence of the RANTES initiation codon (ACCATGA) is an effective ribosomal initiation sequence based on Kozakn enzyme sites in place of the *nef* gene of SHIV-NM3rN. SHIV-NM3rN was constructed from HIV-1 NL432 's report (effective ribosomal initiation sequence: ANNATGN or GNNATGR). SHIV-NI has some unique restrictio(black regions) and SIV mac239 (white regions).

is not thought to be blocked by RANTES. In SHIV-NI, the *nef* gene was replaced by some unique restriction enzyme sites, including the *Cla* I and *Apa* I sites. The human RANTES open reading frame (ORF) was first amplified by PCR from a full length human RANTES cDNA as previously described [20]. The flanking sequence of the RANTES ORF was modified with the PCR primer RAN-Cla (5'-AT*ATCGAT*-ACCATGAAGGTCTCCGCGGCAG-3') and RAN-Apa (5'-TA*GGGCCC*CTAGCTCATCTCCAAAGAGTTG-3'). The underlined ATG in RAN-Cla indicates the start of the RANTES ORF. The relevant restriction sites in each primer are shown in italics. The flanking sequence of the RANTES initiation codon (ACCATGA) corresponds to an effective ribosomal initiation sequence based on Kozak's [21] report (effective ribosomal initiation sequence, ANNATGN or GNNATGR). The PCR product was cloned into pUC119 vector by TA-cloning, and the sequence was confirmed as previously described [22]. The PCR fragment digested with *Cla* I and *Apa* I was inserted into the SHIV-*nef* vector (Fig. 1).

2.2. Cell cultures

A $CD4^+$ human T lymphoid cell line, M8166 (a subclone of C8166), was used to prepare the stock virus and to measure the viral infectivity in human cells [23]. HSC-F cells, a cynomolgus monkey $CD4^+$ T cell line, were used to assess the viral infectivity in monkey cells [24]. PM1, a $CD4^+$ T cell clone that expresses CCR5, was derived from the human neoplastic T cells line Hut78 [25]. C8166-CCR5 cells were established by the transfection of C8166 cells with the human CCR5 coding region using retrovirus vector pMX-puro, which contains a puromycin-resistant gene [26]. PM1 and C8166-CCR5 were utilized as CCR5-expressing cells and R5-tropic

HIV-1-susceptible cells. These cell lines were all maintained in RPMI medium (RPMI 1640 with 2 mM L-glutamine and sodium bicarbonate; Sigma, St. Louis, MO) containing 10% heat-inactivated fetal calf serum (FCS) (Gibco-BRL Life Technologies, Auckland, New Zealand). Puromycin (1 μg/ml, Sigma) was added to the medium as a selection agent for C8166-CCR5 cells.

2.3. Virus stock

SHIV-RANTES and SHIV-NI was propagated as descried previously [22]. The virus stocks of the SHIV-RANTES and SHIV-NI were produced in M8166 cells, and the virion-associated reverse transcriptase (RT) activity of the virus stocks was measured. The titers of the viruses were determined by the 50% tissue culture infectious dose ($TCID_{50}$) method as described by Reed and Muench [27]. The $TCID_{50}$ of virus was correlated with the RT activity in this study. The laboratory monocytotropic HIV-1 BaL was utilized as R5-tropic HIV-1 [28]. The virus stock of HIV-1 BaL was prepared from the culture supernatants of HIV-1 BaL-infected PM1 cells.

2.4. Virus Infection of human and monkey cells

To investigate the kinetics of virus replication and production of RANTES with SHIV-RANTES in human cells, M8166 cells were inoculated with the virus as described elsewhere [22]. The virus inoculum was adjusted to contain a certain amount of RT units by adding the appropriate volume of the medium to the virus stock. Half of the culture supernatant was harvested with subsequent addition of new medium every 3 days. Virus replication kinetics was monitored by the RT activity of the supernatant. The production of RANTES from the virus-infected cells was measured by enzyme linked immunosorbent assay (ELISA) using a Quantikine human RANTES ELISA kit (R & D Systems, Inc., Minneapolis, MN). To assess the properties of SHIV-RANTES in monkey cells, HSC-F cells were also inoculated with the virus.

2.5. Flow cytometric analysis of CCR5 expression

RANTES down-modulates expression of CCR5 on the cell surface [29]. To assess the biological activity of the RANTES produced by virus-infected M8166 cells, the down-modulation of CCR5 in PM1 cells was evaluated. PM1 cells were plated at 2.5×10^5 cells per well, and incubated for 30 min at 37 °C with 100 μl of the culture supernatant of the samples. Thereafter, the cells were harvested and treated in staining buffer [phosphate buffered saline (PBS) containing 2% FCS and 0.1% sodium azide] for 20 min at 4 °C with phycoerythrin-conjugated anti-human CCR5 monoclonal antibodies (MAb) (2D7: PharMingen, San Diego, CA). To inactivate the virus, the cells were fixed in 4% paraformaldehyde for 30 min. Cells were analyzed for the cell surface expression of CCR5 by flow cytometry (EPICS XL ELITE: Beckman Coulter, Miami, FL). The percentage of CCR5 expression was calculated based on the samples without RANTES (0 ng/ml) which was defined as 100%. To assess the effect of the virus particles, the concentrations of the virions in the culture supernatants from the SHIV-RANTES-infected M8166 cells and SHIV-NI-infected cells were adjusted based on the virion associated-RT activity levels. To evaluate the effect of the spontaneous production of RANTES from the M8166 cells, the CCR5 expression on PM1 cells exposed to supernatants from virus-uninfected cells (hereafter referred to Mock) was also monitored. Serial dilutions of recombinant human RANTES (2–200 ng/ml; CHEMICON International, Inc., Temecula, CA) were used as controls. In the blocking assay with the anti-RANTES neutralizing antibodies, the supernatant samples were incubated with 25 μg/ml of MAb anti-human RANTES (R & D Systems) for 30 min at 37 °C before adding the samples to PM1 cells.

2.6. Inhibition of R5-tropic HIV-1 replication with the RANTES produced by SHIV-RANTES

To investigate whether the produced RANTES inhibits R5-tropic HIV-1 infections, the replication of HIV-1 BaL, an R5-tropic HIV-1, was monitored in the presence of the culture supernatants from the SHIV-RANTES-infected cells. The SHIVs in the culture supernatants were inactivated by UV-irradiation at 2 J/cm^2 to exclude the interference of replication of SHIVs on this assay. PM1 cells (5×10^4 cells per well) were incubated with the UV-irradiated samples, and infected with HIV-1 BaL. Half of each culture supernatant of PM1 cells was harvested with subsequent addition of new UV-irradiated samples every 3 days. The replication kinetics of HIV-1 BaL was monitored by the RT assay. To assess the influence of UV-irradiation, a recombinant human RANTES that had been exposed to a UV-source was also used.

2.7. In vitro challenge experiment

To assess whether the pre-inoculation with SHIV-RANTES inhibits R5-tropic HIV-1 replication, the SHIV-RANTES-infected C8166-CCR5 cells were challenged with HIV-1 BaL. C8166-CCR5 cells were pre-infected with SHIV-RANTES or SHIV-NI at 6 days before HIV-1 BaL infection. The inoculation of SHIV-RANTES and SHIV-NI were adjusted to the same RT levels. C8166-CCR5 cells were incubated for 2 h with SHIVs, washed two times with RPMI medium, and then cultured at 5×10^4 cells per well in a 96-well plate. Six days later, the SHIV-NI- and SHIV-RANTES-infected cells were co-infected with HIV-1 BaL. The culture supernatants of the C8166-CCR5 cells were harvested every 3 days. The growth kinetics of HIV-1 BaL and SHIVs was independently monitored with a differentiating real-time PCR quantification assay [2,30]. Total RNAs were prepared from the culture supernatants of virus-infected C8166-CCR5 cells with a QIAamp viral RNA kit (Qiagen,

Germany), and RT-PCR was performed using a TaqMan RT-PCR kit (Perkin–Elmer). The SIV *gag* region of the viral RNAs of SHIV-NI and SHIV-RANTES were amplified using the primers SIVII-696F (5'-GGAAATTACCCAGTACAA-CAAATAGG-3') and SIVII-784R (5'-TCTATCAATTTT-ACCCAAGGCATTTA-3'). A labeled probe SIVII-731T (5'-Fam-TGTCCACCTGCCATTAAGCCCG-Tamra-3') was used to quantify the PCR product. To detect RNA of the challenge virus HIV-1 BaL, nucleotide sequences for the HIV-1 *gag* region were amplified using the primers NL432-gag-F (5'-CAAGCAGCCATGCAAATGTTA-3') and NL432-gag-R (5'-GCATGCACTGGATGCAATCTAT-3'). A labeled probe NL432-gag-T (5'-Fam-AGAGACCATCAATGAGGAA-GCTGCAGAATG-Tamra-3') was added to the reaction mixture. These reactions were performed with a Prism 7700 Sequence Detector (Applied Biosystems, Foster City, CA) and analyzed using the manufacturer's software. The viral RNA loads were quantified based on the copy number of the standard samples.

2.8. Stability of SHIV-RANTES after serial passages in vitro

SHIV-RANTES was inoculated to M8166 cells at 5×10^5 cells per well in a 24-well plate. When the cytopathic effect (CPE) was confluent, half of each culture supernatant was used to infect a well containing fresh M8166 cells. The culture supernatants from SHIV-RANTES-infected cells were passaged 10 times in this way. To analyze the inserted RANTES genes in SHIV-RANTES, the proviral DNA was amplified from the virus-infected cells after each passage and the length of the RANTES flanking region were checked by PCR [31].

3. Results

3.1. Replication of SHIV-RANTES and production of RANTES in human and monkey cells

In this study, a chimeric simian–human immunodeficiency virus having RANTES gene (SHIV-RANTES) was constructed (Fig. 1). SHIV-RANTES replicated well in human M8166 cells with almost the same replication competence as parental SHIV-NI (Fig. 2A). The RT activity of SHIV-RANTES peaked at about 9 days post infection (d.p.i.). The maximum level of RANTES in the culture supernatants was 98.5 ng/ml for the SHIV-RANTES-infected M8166 cells. The spontaneous production of RANTES was detected at levels between 4.1 and 9.3 ng/ml in the SHIV-NI-infected M8166 cells and the virus-uninfected M8166 cells control. Replication of SHIV-RANTES in monkey HSC-F cells, reached a peak at about 15 d.p.i. (Fig. 2B). The replication kinetics of SHIV-RANTES was similar to that of SHIV-NI. The maximum level of RANTES in the culture supernatants from SHIV-RANTES-infected HSC-F cells was at 4.1 ng/ml,

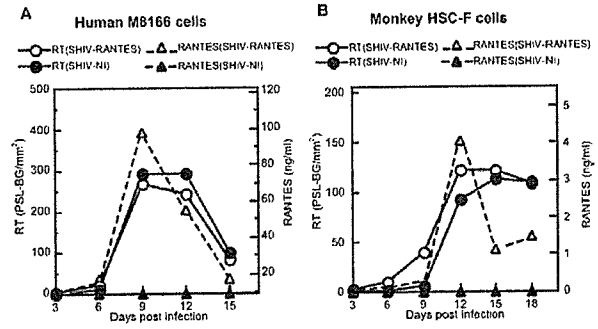

Fig. 2. Kinetics of virus replication and RANTES production with SHIV-RANTES and SHIV-NI in human (A) and monkey (B) $CD4^+$ cell lines. Viral replication was monitored by RT activity in the supernatant of cell cultures infected with SHIV-RANTES (open circles) or SHIV-NI (closed circles). The unit for RT activity is PSL-BG, photo-stimulated luminescence minus background (FLA-3000, Fuji Film, Japan). RANTES production (ng/ml) was detected by ELISA in the supernatant of cell cultures infected with SHIV-RANTES (open triangles) or SHIV-NI (closed triangles).

while it was less than the cut-off value (0.094 ng/ml) in the culture supernatants from the SHIV-NI-infected cells. SHIV-NI and SHIV-RANTES used CD4 and CXCR4, but not CCR5, as determined by an infection of GHOST cells expressing CXCR4 or CCR5 (data not shown). These data show that RANTES was produced efficiently along with the replication of SHIV-RANTES in human and monkey cells, and that the replications of SHIV-RANTES, X4-tropic virus, was not influenced by its production of RANTES.

3.2. Down-modulation of CCR5 by RANTES

RANTES down-modulates CCR5 from the cell surface, and CCR5 reaccumulates on the cell surface after the removal of ligands [29,32]. To check the biological activity of the produced RANTES, the down-modulation of CCR5 on PM1 cells was monitored. Surface expression of CCR5 was detectable on approximately 21% of PM1 cells with the anti-CCR5 MAb 2D7, which is consistent with a previous report [33]. In this study, the levels of RANTES in the cultures infected by SHIV-RANTES, SHIV-NI, and Mock were 14, 2.6, and 2.6 ng/ml, respectively. Treating the cells with recombinant human RANTES reduced expression of CCR5 on the cell surface in a dose-dependent manner (Fig. 3). When the PM1 cells were incubated with the culture supernatants from the SHIV-RANTES-infected cells, CCR5 expression on the cell surface was consistently reduced about 75%. Down-modulation of CCR5 was also observed in the cells treated with the culture supernatants from the SHIV-NI-infected cells, but the reduction was only about 33%, which was less than that in cells treated with culture supernatants from the SHIV-RANTES-infected cells. The down-modulation of CCR5 with the sample from the SHIV-NI-infected cells is thought to be due to the background concentration of RANTES, since the reduction was almost the same as that treated with the samples from the Mock (the down-modulation of CCR5 was 34%). Pretreatment of the samples with the anti-RANTES antibody

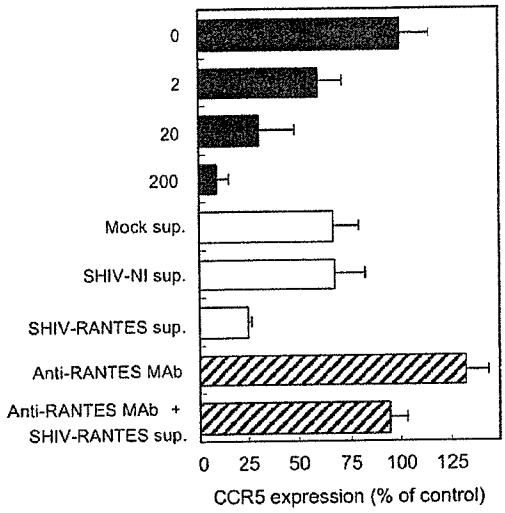

Fig. 3. Down-modulation of CCR5 on the surface of PM1 cells by RANTES. White bars, CCR5 expression on PM1 cells exposed to supernatant from cells infected with SHIV-RANTES, SHIV-NI, and uninfected cells (Mock). Black bars, PM1 cells treated with recombinant human RANTES at the indicated concentrations (in ng/ml). Hatched bars, cells treated with anti-RANTES antibody (Anti-RANTES MAb). These data are expressed as the mean of triplicate experiments ± S.E.M.

completely abolished the down-modulation of CCR5. Thus, the reduction of the cell surface CCR5 correlates with the level of the expressed RANTES from SHIV-RANTES-inoculated cells.

3.3. Inhibition of R5-tropic HIV-1 BaL infection by RANTES from SHIV-RANTES-inoculated cells

In this study, the levels of RANTES in the UV-irradiated samples from the cultures infected with SHIV-RANTES, SHIV-NI, and Mock were 14, 0.8, and 0.8 ng/ml, respectively. In the case of the culture supernatants from SHIV-RANTES-infected cells, approximately 51% of the inhibition of HIV-1 BaL infection was consistently observed at 12 d.p.i., when the viral loads of the HIV-1 BaL peaked (Fig. 4). A reduction of the HIV-1 BaL RT activity was also observed for the culture supernatants from the SHIV-NI-inoculated cells and that of the Mock-inoculated cells, but the reductions were only about 23% and 20%, respectively. Interestingly, inhibition of HIV-1 BaL infection with the 14 ng/ml of the produced RANTES from the SHIV-RANTES-infected cells (51% inhibition) was slightly greater than inhibition with an equal concentration of recombinant human RANTES (42% inhibition). These results suggest that the produced RANTES efficiently inhibits R5-tropic HIV-1 infection.

3.4. In vitro challenge experiments of the SHIV-RANTES inoculated cells with R5-tropic HIV-1

A previous finding in the SIV-macaque models suggested that the induction of a CC-chemokine by a recombinant SIV

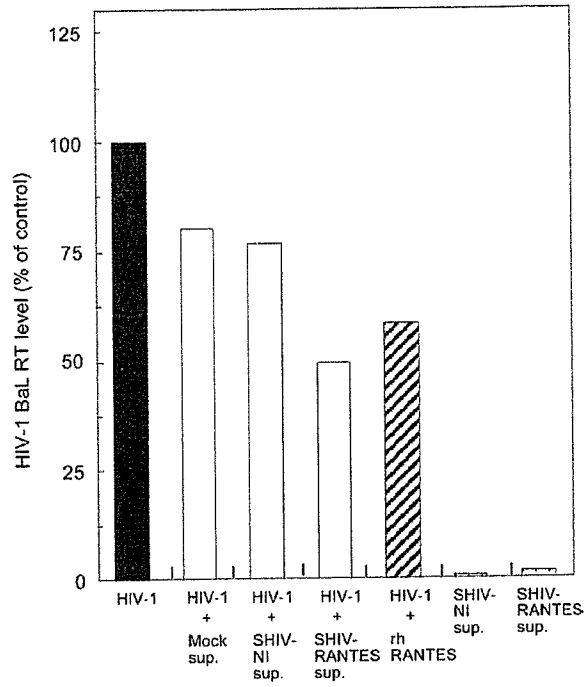

Fig. 4. Inhibition of HIV-1 BaL by UV-irradiated culture supernatants from SHIV-RANTES-infected cells. Virus replication of HIV-1 BaL was monitored by RT activity from the culture supernatants of virus-infected PM1 cells at 12 d.p.i. As control, cells treated with the same concentrations of UV-irradiated recombinant human RANTES were monitored (HIV-1 + rh RANTES). UV-irradiated supernatants from SHIV-RANTES and SHIV-NI-infected cells without HIV-1 BaL infection were used as negative controls. These data show one of three independent experiments with similar results.

vaccine was associated with protective immunity to mucosal infection with SIV [34]. We assessed whether the pre-inoculated cells with SHIV-RANTES were protected against the challenge with R5-tropic HIV-1 in in vitro experiments. In this assay, C8166-CCR5 cells were used as CCR5 positive cells, since the ability of virus replication in C8166-CCR5 cells was better than that in PM1 cells. As shown in Fig. 5A,B, the SHIV-RANTES-inoculated C8166-CCR5 cells produced RANTES, reaching a maximum level of 66.7 ng/ml at 6 days post challenge (d.p.c.) (at 12 d.p.i.). At the time of the challenge with HIV-1 BaL, the RANTES level in the culture supernatant of SHIV-RANTES-infected cells was already 16.9 ng/ml, while that of the SHIV-NI-infected cells was less than the cut-off value (2.5 ng/ml) during the experiment.

As shown in Fig. 5B, the viral loads of HIV-1 in the naive HIV-1 BaL-infected C8166-CCR5 cells increased to above 10^7 copies per ml at 9 d.p.c., and remained at a high level. Pre-inoculation of SHIV-RANTES suppressed the challenge of HIV-1 BaL. The peak virus loads of HIV-1 BaL in the SHIV-RANTES pre-inoculated C8166-CCR5 cells were two orders of magnitude lower than that of the naive HIV-1 BaL-inoculated cells. The viral loads of HIV-1 BaL in the culture supernatants of the SHIV-RANTES pre-inoculated cells plateaued at 10^4 copies per ml during the observation period. Viral loads of HIV-1 BaL in the SHIV-NI pre-infected cells reached between 10^5 and 10^6 copies per ml, which is higher

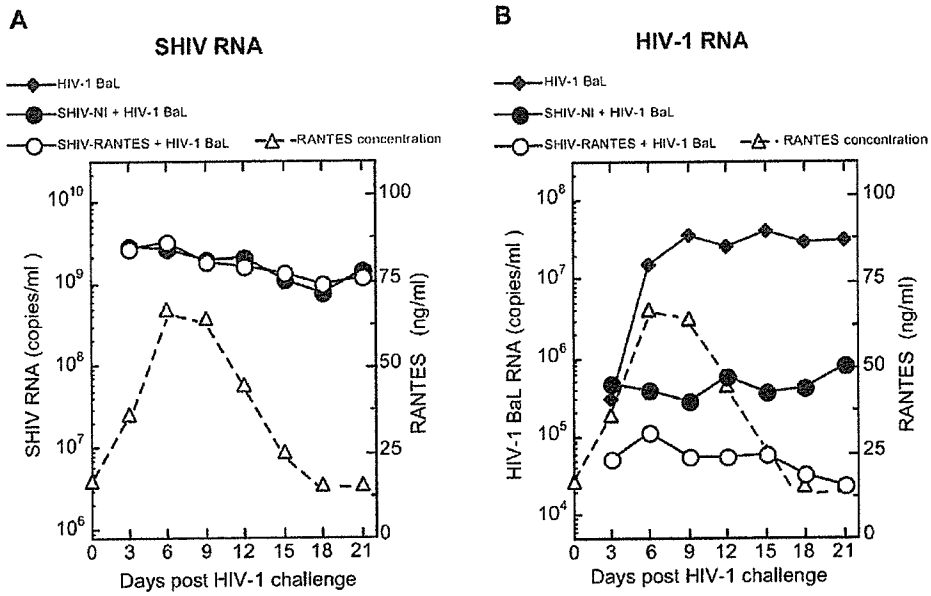

Fig. 5. Suppression of HIV-1 BaL by the pre-inoculation of SHIV-RANTES. Cells were pre-inoculated with SHIV-RANTES (open circles) and SHIV-NI (closed circles) at 6 days before the challenge of HIV-1 BaL. The HIV-1 BaL-infected cells without a pre-inoculation of SHIVs were used as a naive control (closed diamonds). Viral RNA levels of HIV-1 BaL and SHIVs were independently monitored by real-time RT-PCR using specific primer sets for either SIV *gag* region (A) or HIV *gag* region (B). Open triangles indicate RANTES levels produced by SHIV-RANTES, as determined by ELISA. (The RNA level of HIV-1 BaL detected by the primer for the SIV *gag* region was below 10^6 copies per ml).

than that in the SHIV-RANTES pre-inoculated cells. These results show that pre-inoculation of C8166-CCR5 with SHIV-RANTES partially protected against the challenge with HIV-1 BaL in vitro.

3.5. Stability of inserted RANTES gene in SHIV

Insertion of an additional gene may be a burden for the virus itself. In other studies, some cytokine genes such as IFN-γ, IL-2, and IL-12 inserted into either SHIV or SIV were found to be deleted during long-term experiments [19,35,36]. The stability of the inserted RANTES fragments in SHIV-RANTES after serial passage was examined by PCR of proviral DNA. These experiments were done more than three times. As shown in Fig. 6A, the inserted RANTES gene was found to be stable for at least 10 passages. The peaks of RANTES production in the culture supernatants from passage 1, 5, and 10 in the SHIV-RANTES-infected cells were 78.9, 76.8, and 82.2 ng/ml, respectively (Fig. 6B). These results show that SHIV-RANTES retained the ability to produce RANTES after serial passages. Furthermore, the expressed RANTES retained its ability to down-modulate CCR5 and to protect against HIV-1 BaL infection after 10 passages (Fig. 6C,D). These results show that the inserted RANTES gene in SHIV-RANTES was functional and stable until at least the 10th passage.

4. Discussion

In this paper, we compare the in vitro properties of SHIV-RANTES with those of its parental SHIV-NI. SIV/SHIV vectors containing a cytokine gene appear to be appropriate tools for observing the effect of local production of a cytokine on virus replication, pathogenesis, and immunogenicity, especially because the inserted cytokine gene is expressed in the region where the SIV/SHIV vector replicates. Because SIV dominantly utilized CCR5 for the virus entry and RANTES would suppress its replicate, we used the SHIV-NM3rN having the Env of X4-tropic HIV-1 NL432 as a vector that expresses RANTES genes. As expected, the replication of SHIV-RANTES, X4-tropic SHIV, was not suppressed by the expressed RANTES in this experiment.

SHIV-RANTES replicated well not only in the human $CD4^+$ T cell line M8166 but also in the monkey $CD4^+$ T cell line HSC-F. In addition, SHIV-RANTES successfully replicated in monkey PBMCs (data not shown). The expression level of RANTES in human M8166 cells was very high (up to 98.5 ng/ml). The high level of expression of RANTES may be partly due to the introduction of an effective ribosomal binding sequence at the flanking region of the RANTES ORF [21] and partly due to inserting the gene at the *nef* region [37]. We previously constructed the SHIV-*vpr* vector, named SHIV-3sj, from the same parental SHIV-NM3rN. Insertion of the RANTES gene into SHIV-3sj resulted in the expression of RANTES at a maximum level of 47.4 ng/ml in the culture supernatants of virus-infected M8166 cells [20]. The expression of RANTES with the SHIV-*nef* vector was about two times higher than that with the SHIV-*vpr* vector. A high level of expression of RANTES is advantageous to study the adjuvant effect of RANTES in vivo.

The results of many studies indicate that RANTES and its analogues suppress the infection of R5-tropic lentiviruses in

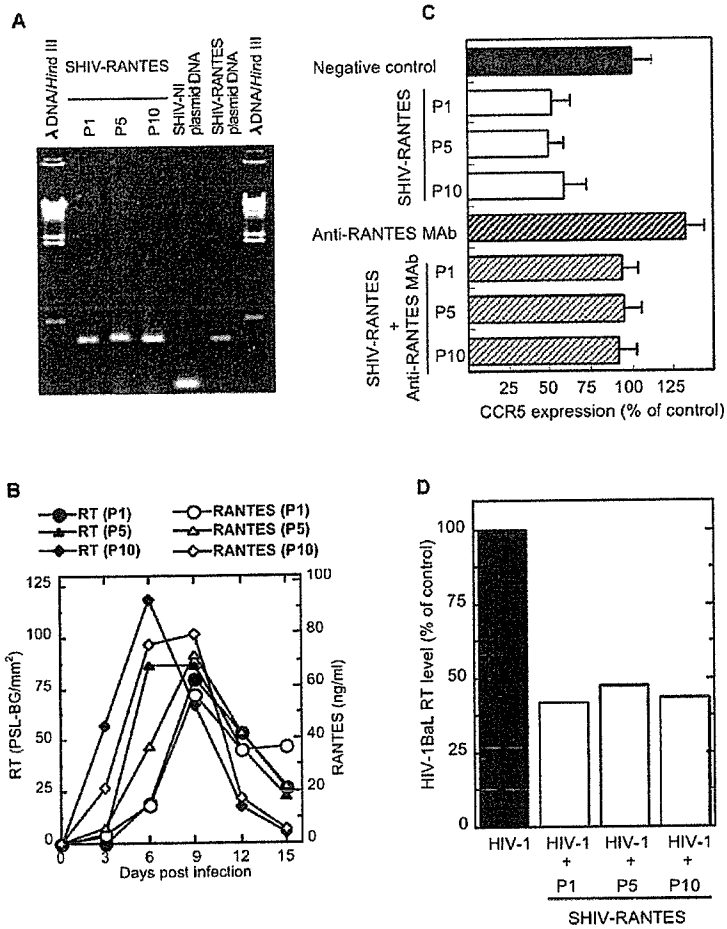

Fig. 6. Stability of SHIV-RANTES with serial passage. Culture supernatants from cells infected with SHIV-RANTES at passage 1 (P1), 5 (P5), and 10 (P10) were used for the experiments. (A) Stability of the inserted RANTES fragment in SHIV-RANTES was examined by PCR. DNA plasmids of SHIV-NI and SHIV-RANTES were used as the templates of the control. A λ DNA digested with *Hind* III was used as a size marker. (B) Kinetics of the RT activity and expression of RANTES at different passages. The unit for RT activity is PSL-BG, photo-stimulated luminescence minus background (FLA-3000, Fuji Film, Japan). The unit for RANTES (ng/ml) was determined by ELISA. (C) Down-modulation of CCR5 by RANTES expressed at different passages. The samples were also treated with anti-RANTES antibody to confirm the specificity of RANTES. (D) Inhibitory effect of R5-tripoc HIV-1 BaL replication by RANTES produced by a serial passage of SHIV-RANTES.

vitro. However, little information is available on the role of RANTES on X4-tropic lentivirus replication. Previous studies reported that RANTES enhanced X4-tropic and R5X4-tropic HIV-1 replication, both of which depend on a signal transduction and the enhanced HIV-1 replication is associated with increased colocalization of CD4 and CXCR4 [38]. The over-expression of RANTES may increase the replication of X4-tropic SHIV. A safety concern about live-attenuated viruses is that their replication rate may increase. In vitro, however, we did not observe increased SHIV replication in either human or monkey cell lines infected with the RANTES-producing virus.

Although the goal of this study is to test the immune-modulating effect of RANTES against HIV-1-related virus infection, immune responses are difficult to assess in in vitro experiments. In vitro, the inhibitory effects of RANTES on the entry of R5-tropic strains of lentivirus are well established. RANTES blocks or down-modulates CCR5 in vitro, which suppresses HIV-1 infections [29,32]. The down-modulation of CCR5 is a biological activity of RANTES. Our findings that the produced RANTES down-modulated CCR5 expression on the cell surface of PM1 cells and that UV-treated samples from SHIV-RANTES-infected cells partially protected the PM1 cells from the R5-tropic HIV-1 BaL infection suggest that RANTES expressed by SHIV-RANTES-infected cells is the factor protecting against R5-tropic HIV-1 infection. In this study, the biological activity of RANTES was confirmed by its ability to down-modulate expression of CCR5 and to inhibit the R5-tropic HIV-1 BaL infection.

Our finding that the viral growth kinetics of HIV-1 BaL was more strongly inhibited by the RANTES produced by SHIV-RANTES-infected cells than by the recombinant RANTES may be due to the presence of inactivated virus particles and other inhibitory factors in the culture supernatants of the SHIV-RANTES-inoculated cells. Another reason

is that the RANTES produced by mammalian cells is structurally different from the recombinant RANTES. RANTES is secreted from some cells as a macromolecular complex containing sulfated proteoglycans (with molecular sizes of 400–600 kDa), whereas the molecular size of recombinant RANTES is approximately 7.8 kDa [39,40]. The interaction of chemokines with proteoglycans enhances their anti-HIV-1 activity [40,41]. In this experiment, after the separation into < 100 kDa fractions by ultrafiltration (UF) membranes, the concentration of the produced RANTES was reduced to 1.6% of the pre-filtered levels (from 39.3 to 0.61 ng/ml) (data not shown). Many studies have used recombinant RANTES to determine the role of RANTES in HIV-1 infection. In our SHIV-*nef* vector system, the RANTES is produced in a natural, secreted form, which may be an advantage for studying the effect of RANTES in vivo.

The immune responses induced by an attenuated virus can increase the immunity to a pathogenic virus. Compared with the immunostimulatory cytokines produced by other *nef* deletion mutants, the RANTES produced by SHIV-RANTES is expected to not only boost the primitive non-specific immunity and virus-specific immune response but also directly inhibit the entry of R5-tropic virus to susceptible cells. SHIV-RANTES has an ability to protect against challenge with a pathogenic virus when inoculated to monkeys. Indeed, we found that HIV-1 BaL replication was two orders of magnitude lower in the cells pre-inoculated with SHIV-RANTES than in the naive HIV-1 BaL-inoculated cells.

In conclusion, we have established a SHIV-*nef* vector system that stably expresses a high level of biologically active RANTES. Inoculation of macaque monkeys with SHIV-RANTES should provide further information on the immune-modulating effects of RANTES against lentiviral infections.

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Isolation of the Feline α1,3-Galactosyltransferase Gene, Expression in Transfected Human Cells and its Phylogenetic Analysis

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ABSTRACT The enzyme alpha 1,3-galactosyltransferase (α1,3-GT), which catalyzes synthesis of terminal α-galactosyl epitopes (Gal α1,3Gal β1-4GlcNAc-R), is produced in non-primate mammals, prosimians and new-world monkeys, but not in old-world monkeys, apes and humans. We cloned and sequenced a cDNA that contains the coding sequence of the feline α1,3-GT gene. Flow cytometric analysis demonstrated that the α-galactosyl epitope was expressed on the surface of a human cell line transduced with an expression vector containing this cDNA, and this α-galactosyl epitope expression subsided by α-galactosidase treatment. The open reading frame of the feline α1,3-GT cDNA is 1,113 base pairs in length and encodes 371 amino acids. The nucleotide sequence and its deduced amino acid sequence of the feline α1,3-GT gene are 88–90% and 85–87%, respectively, similar to the reported sequences of the bovine, porcine, marmoset and cebus monkey α1,3-GT genes, while they are 88% and 82–83%, respectively, similar to those of the orangutan and human α1,3-GT pseudogenes, and 81% and 77%, respectively, similar to the murine α1,3-GT gene. Thus, the α1, 3-GT genes and pseudogenes of mammals are highly similar. Ratios of non-synonymous nucleotide changes among the primate pseudogenes as well as the primate genes are still higher than the ratios of non-primates, suggesting that the primate α1,3-GT genes tend to be divergent. *J. Exp. Zool. (Mol. Dev. Evol.) 306B:59–69, 2006.*

Alpha 1,3-galactosyltransferase (α1,3-GT) (EC 2.4.1.151) is responsible for the synthesis of terminal α-galactosyl epitopes (Gal α1,3Gal β1-4GlcNAc-R) in sugar chains. These epitopes are produced by non-primate mammals, prosimians and new-world monkeys and are found on the cell surface ($>10^6$ epitopes/cell) as well as in secreted glycoproteins. The full-length α1,3-GT sequences of human and orangutan (Koike et al., 2002) and some partial sequences, similar to α1,3-GT genes of non-primate mammals, have been detected in humans and higher primates (Larsen et al., '90; Joziasse et al., '91). These sequences have been judged to be pseudogenes because of the generation of premature stop codons due to multiple base deletions (Larsen et al., '90; Joziasse et al., '91; Koike et al., 2002). The expression of α1,3-GT protein is not detected in humans and other catarrhines (Spiro and Bhoyroo, '84; Galili et al., '87, '88; Thall and Galili, '90), thus resulting in the production of large amounts of a natural antibody against the α-galactosyl epitope (Galili et al., '84, '87).

The α1,3-GT is a Golgi membrane-bound enzyme that catalyzes the addition of α-galactosyl epitopes to existing β-galactose terminals accord-

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ing to the following reaction (Basu and Basu, '73; Blanken and Van den Eijnden, '85; Elices et al., '86): UDP galactose+β-D-galactosyl-1,4-*N*-acetyl-D-glucosaminyl-R→ UDP+α-D-galactosyl-1,3-β-D-galactosyl-1,4-*N*-acetyl-D-glucosaminyl-R, in which R may be a glycoprotein or a glycolipid. α1,3-Galactose and less abundant α1,6-linked galactose can be cleaved by the enzyme α-galactosidase (EC 3.2.1.22).

The whole mRNA for α1,3-GT has been found in cells of non-primate mammals and marmoset (Joziasse et al., '89; Larsen et al., '89; Henion et al., '94; Strahan et al., '95; Koike et al., 2002), but only partial mRNAs have been detected in those of old-world monkeys (OWM) (rhesus monkey, green monkey and patas monkey) or human cells (Joziasse et al., '89; Joziasse, '92), indicating that the regulatory sequences can still be functional. Several homologs of the α1,3-GT gene have been described in the human genome, but all of them contain several frame-shift mutations that lead to the generation of premature internal stop codons (Larsen et al., '90; Joziasse et al., '91). One homolog is thought to correspond to the original α1,3-GT gene because it contains intronic sequences (Joziasse et al., '91) as well as one exonic sequence corresponding to the largest part of the catalytic domain of the enzyme (Larsen et al., '90), and this gene has been localized on chromosome 9. Another one, which does not contain any intronic sequences and is located on chromosome 12, corresponds to a copy of the α1,3-GT gene (Larsen et al., '90; Joziasse et al., '91). This pseudogene has also been found in apes and OWM (Galili and Swanson, '91).

By Northern blot analysis, 3.6–3.9 kb α1,3-GT transcripts are detected in bovine and marmoset cells, but not detected in human and OWN cells (Joziasse et al., '89). For the first time, Koike et al. (2002) have detected the full-length sequences of α1,3-GT of orangutans and humans using sensitive PCR-based methods. Comparison of the deduced amino acid sequences with the marmoset gene sequence has revealed that in the human α1,3-GT pseudogene sequence, three single-nucleotide deletions are present at the site corresponding to the amino acid positions 81, 256 and 284 of marmoset α1,3-GT protein, and result in the appearance of the stop codons at positions 268 and 362. Thus, only non-functional proteins are made even when the full-length mRNA is overexpressed and translated in human cells.

A study on the murine α1,3-GT gene has revealed that it is distributed over nine exons that span at least 35 kb of the genomic sequence (Joziasse, '92). Transcription of this gene results in the production of four distinct mRNAs that are generated by the alternative splicing. Translation of these individual mRNAs produces four related isoforms of α1,3-GT consisting of 337, 349, 359 and 371 amino acids.

In this study, we have described the isolation and characterization of a cDNA clone comprising the complete coding sequence of feline (cat) α1, 3-GT that is capable of catalyzing the synthesis of α-galactosyl epitopes on human cells. Phylogenetic analysis was performed to evaluate the evolutionary relationship among the six different full coding sequences of α1,3-GT genes and two pseudogenes.

MATERIALS AND METHODS

Cell culture

8C feline kidney cells (Fischinger et al., '73) were cultured in Eagle's minimum essential medium (EMEM) supplemented with 10% fetal calf serum (FCS) at 37°C under 5% CO_2 in humidified air. A human osteosarcoma cell line, HOS, infected with a Melanesian strain of human T-cell leukemia virus type I (HTLV-I), termed HOS/HTLV-I_{MEL5}, was cultured in Dulbecco's modified EMEM (Hoshino et al., '93).

Reverse transcriptase-polymerase chain reaction

When 8C cells became confluent, they were collected in an Eppendorf tube using a scraper. Total RNA was isolated from 8C cells using an RNA extraction kit, SepaGene (Sanko-Junyaku Co. Ltd., Tokyo, Japan), according to the manufacturer's protocol. cDNA was synthesized using total cellular RNA as the template, using the SuperScript™ Preamplification System for First-Strand cDNA Synthesis kit (GibcoBRL, Life Technologies™, Carlsbad, CA) in accordance with the manufacturer's protocol. PCR was used to amplify the α1,3galactosyltransferase gene in cDNA preparation. Two sets of primers were used for PCR. One set was made according to the porcine α1,3-GT sequence as follows: 5′-AT GAATGTCAAAGGAAGAGTGGTTCTGTCA-3′ as a forward primer and 5′-TCAGATGTTATTTC TAACCAAATTATACTC-3′ as a reverse primer. The other set was designed using DNA sequences of α1,3-GT of pig (Strahan et al., '95), mouse (Larsen et al., '89), cow (Joziasse et al., '89) and

marmoset (Galili et al., '88). Namely, the regions where the nucleotide sequences of α1,3-GT are well conserved were selected and used to make PCR primers as follows: 5′-GGAGAAAATAAT GAATGTCAA-3′ as a forward primer and 5′-TCAGATGTTATTTCTAACCAAATT-3′ as a reverse primer. The initiation and stop codons in the primers are underlined.

Cloning of the feline α1,3-GT and sequencing

The PCR product was cloned into a TA cloning vector, pCR2.1 (Invitrogen, Carlsbad, CA), and the ligated product was used to transform DH5α *E. coli* strain. *E. coli* colonies were tested for mini-scale plasmid preparation, and colonies containing a 1.1 kb insert after multiple enzyme digestion were selected. Clones containing inserts were sequenced using Texas Red-labeled M13 forward and reverse primers for sequencing DNA. A Hitachi SQ-5500 automated DNA sequencer and software (Hitachi, Tokyo, Japan) were used to determine DNA sequences as described previously (Jinno et al., '98). The plasmid vector pCR2.1 containing the insert and the expression vector pcDNA3 (Clontech Co., Palo Alto, CA) were digested with *BamH*I and *Not*I and purified. The insert in the pCR2.1 vectors was then re-ligated to the digested pcDNA3 vector DNA. After transformation of competent cells, DH5α, by this ligation product, plasmids purified from colonies contained an insert of about 1.1 kb. It was confirmed by enzyme digestion of the plasmid DNA with *Stu*I, *Spe*I, *BamH*I and *Stu*I that the inserts were in a correct direction (data not shown).

Transfection of the feline α1,3-GT gene and detection of its expression

The mammalian expression vector pcDNA3 harboring the gene of the feline α1,3-GT was transfected into a clonal line of HTLV-I-infected HOS cells using LipofectAMINE (GibcoBRL) to examine the effects of α1,3-GT expression on HTLV-I infection, and neomycin-resistant cells were selected as described elsewhere (Jinno et al., '98). In short, the cells were seeded at 4×10^5 cells/ml/well into 12-well plates and incubated overnight. The cells in nine wells were independently transfected with pcDNA3 DNA harboring the gene of the feline α1,3-GT or pcDNA3 DNA alone using LipofectAMINE (GibcoBRL). The cells were selected with neomycin after 24 hr incubation and maintained for 3 weeks. The expression of α-galactosyl epitope on the surface of HOS and HOS/HTLV-I cells and feline cells was detected by flow cytometry (FCM) (Cyto ACE-100, Auto cell screener, Japan Spectroscopic Co., Ltd.) after treatment with fluorescent isothiocyanate labeled *Bandeiraea simplicifolia* Isolectin B_4 (FITC/BS-IB_4) (Sigma Chemical Co., St. Louis, MO) (Wood et al., '79; Azimzadeh et al., '97; Bracy et al., '98). Briefly, cells were collected into Eppendorf tubes from cultured plates, washed with washing solution (cold PBS with 1% FCS and 0.01% NaN3), pelleted by centrifugation at 5,000 rpm for 5 min and treated for 1 hr with diluted FITC/BS-IB_4 (3.3 pg/ml) on ice. The cells were washed and fixed with 1% paraformaldehyde and analyzed by FCM. In seven (#1–#7) out of nine wells seeded with the feline α1,3-GT-transduced cells, 20–45% of cells were positively stained with FITC/BS-IB_4 (Table 1). These cells were cloned using 96-well plates by seeding 1 cell/well and thus obtained clones were screened again by FCM.

α-Galactosidase treatment

Cells were treated with α-galactosidase as described by Bracy et al. ('98). Briefly, cells were seeded at 4×10^5 cells/well into 6-well plates in 2 ml and incubated overnight. The culture medium was replaced with fresh medium and the cells were incubated for another day. The cells were collected into two Eppendorf tubes from each cultured plate, washed with the washing solution

TABLE 1. Flow cytometry of the cells transfected with the feline α1,3-GT gene

Cell	BS-IB4-positive cells (%)
HOS/HTLV-I	4
HOS/HTLV-I/pcDNA3	5
HOS/HTLV-I/fGT	
#1	45
#2	44
#3	38
#4	32
#5	27
#6	27
#7	22
#8	4
#9	4

Human HOS/HTLV-I cells in nine culture wells were transfected with the feline α1,3-GT gene independently. Neomycin-resistant cells were selected. These HOS cells were processed for FCM using FITC/BS-IB4 lectin and examined for the expression of α-galactosyl epitope on the cell surface. HOS/HTLV-I/pcDNA3 cells were used as a control negative for terminal α1,3-galactose. The cut-off value for FCM was set at the fluorescence intensity that gave 5% positive for the control cells as shown in Figs. 1 and 2.

and pelleted by centrifugation at 5,000 rpm for 5 min. One of them was treated with α-galactosidase dissolved in sodium citrate/phosphate buffer, and the other tube was treated only with buffer for 1 hr at 37 °C. The cells were washed with the washing solution and treated for 1 hr with FITC/BS-IB_4 on ice. The cells were washed and fixed with 1% paraformaldehyde and analyzed by FCM.

Synonymous (K_S) and non-synonymous (K_A) nucleotide substitutions per site

The number of synonymous substitutions per possible synonymous site (K_S) and the number of non-synonymous substitutions per possible non-synonymous site (K_A) (Li et al., '85; Li, '93) were calculated for codons of full-length α1,3-GT gene and pseudogene sequences using MEGA 2.1 (Kumar et al., 2001). K_A/K_S ratios less than 1.0 are generally considered as evidence that the proteins have evolved under negative or purifying selection; pairwise comparisons between active genes show this pattern (Wolfe and Sharp, '93; Endo et al., '96). K_A/K_S ratios over 1.0 suggest positive or directional selection.

Phylogenetic trees for the α1,3-GT isolates

Two phylogenetic trees using the amino acid sequences and nucleotide sequences of the α1, 3-GT cDNAs were constructed using the N–J method (Saitou and Nei, '87), and the reliability of the clusters obtained was evaluated by means of 1,000 bootstrap replicates. The MEGA 2.1 software was used to make the trees.

RESULTS

Isolation of feline α1,3-GT cDNA

A feline kidney cell line, 8C, was used to make α1,3-GT cDNA. Cellular RNA was isolated and reverse transcribed. PCR with the two sets of primers described above was used to amplify cDNA. The PCR product was then ligated with the cloning vector pCR2.1 and the construct was used to transform *E. coli* cells. Plasmid DNAs were isolated from *E. coli* colonies that harbored DNA with the expected length of the insert and used for DNA sequencing. We sequenced seven different clones, and six out of seven clones gave overlapping nucleotide sequences. The full-length coding sequence of the feline α1,3-GT gene was 1,113-bp long (GenBank accession number AY167024) and the deduced amino acid sequence contained 371 amino acids. Its molecular mass was calculated to be 43,568 Da.

Expression of α-galactosyl epitope on the cell surface

The expression vector pcDNA3 with the feline α1,3-GT insert was made and transfected into a cloned human osteosarcoma cell line, HOS, infected with HTLV-I, i.e., HOS/HTLV-I (Hoshino et al., '93) in nine culture wells, and neomycin selection was done. The cells were maintained about 3 weeks in neomycin-containing medium and examined by FCM using fluorescent isothiocyanate-labeled *B. simplicifolia* Isolectin B_4 (FITC/BS-IB_4). In the first screening, FCM results showed that 20–45% cells derived from seven (#1–#7) out of nine wells containing the feline α1,3-GT plasmid-transfected cells were positively stained with FITC/BS-IB_4 (Table 1). The cells derived from wells #1 and #2 were single-cell cloned by seeding them into 96-well plates at a density of one cell per well, and thus obtained two of 19 clones were about 98% positive by FCM (Fig. 1). The clones derived from initial #1 and #2 wells were designated as HOS/HTLV-I/fGT#1-a and #2-a. The surface expression of α-galactosyl epitopes was stable as it was detected by FCM even after 20 cell passages (data not shown). In contrast, the surface expression of α-galactosyl epitopes was not detected upon FCM of untransfected or only pcDNA3 vector-transfected cells. When the feline α1,3-GT-transduced HOS/HTLV-I cells were treated with α-galactosidase, specific reduction of α-galactosyl epitope expression was detected (Fig. 2) by staining with FITC/BS-IB_4 as compared with results of these cells treated with buffer alone. These findings indicated that the cDNA cloned from 8C cells really coded for the feline α1,3-GT. The cells for highly positive α-galactosyl epitopes grew as well as untransfected HOS/HTLV-I cells, and their morphology was indistinguishable from that of the untransfected HOS/HTLV-I cells.

Analysis of the feline α1,3-GT gene sequence

We aligned the deduced amino acid sequences of the α1,3-GT genes of feline, porcine, murine, bovine, cebus and marmoset origins and the human and orangutan α1,3-GT pseudogenes using software for multiple alignments, Clustal W (Thompson et al., '94) (Fig. 3). In our alignment of the amino acid sequences of the eight α1,3-GT genes, the feline sequence was 85–87% similar to

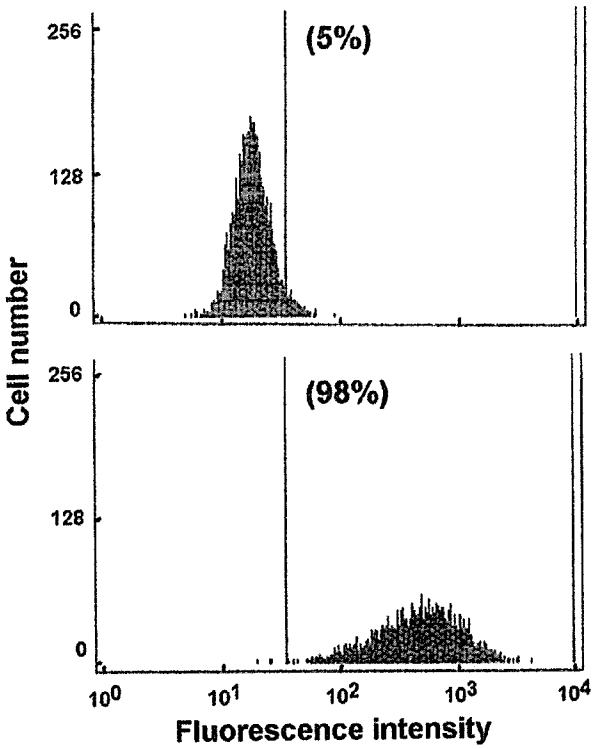

Fig. 1. Detection of α-galactosyl epitope expression. The pcDNA3 control vector-transfected HOS/HTLV-I cells (A) and the feline α1,3-GT gene-transfected HOS/HTLV-I cells (B) were processed for FCM using FITC/BS-IB_4 and examined for the expression of α-galactosyl epitope on the cell surface. The cut-off value for fluorescence intensity was set as 5% of control cells were scored positive (A); the cells that showed stronger intensity than the cut-off value were considered to be positive (B).

those of bovine, porcine, cebus and marmoset origins; the human and orangutan sequences were 82–83% and the murine sequence was 77% similar to the feline sequence. The nucleotide sequences of the bovine, porcine, marmoset and cebus α1, 3-GT genes and of the orangutan and human α1, 3-GT pseudogenes showed a high similarity (88–90%) to the feline sequence, while the murine sequence was only 81% similar to it (Table 2).

Figure 3 shows that there is an especially high similarity among all eight α1,3-GT sequences after amino acid number 84 (feline), 85 (porcine), 85 (murine), 81 (bovine), 89 (human), 89 (cebus), 89 (orangutan) and 90 (marmoset): there was 82–91% similarity in the domain corresponding to amino acid numbers 84–370 of the feline sequence, while in the domain 1–83 the similarity was much lower and between 65% and 72% (Table 2). The highly similar domain has been thought to encode catalytic activities (Henion et al., '94). Although the human and orangutan α1,3-GT genes are inactive, we still noticed the high similarity in their nucleotide sequences with those of other animal α1,3-GT genes. The murine sequence showed a slightly lower similarity: 82% in the 84–370 domain and 62% in the 1–89 domain (Table 2).

To study the evolutionary forces that have been operated among α1,3-GT genes, we analyzed their sequences for synonymous substitution per site (K_S) and non-synonymous substitution per site (K_A) between paired species using the modified Nei–Gojobori method (Kumar et al., 2001). The total number of possible synonymous sites in an individual sequence among the eight α1,3-GT gene sequences was between 287 and 296 (standard error between 6 and 8) with an average of 292, and the total number of possible non-synonymous sites was between 795 and 810 (standard error between 7 and 16) with an average of 803 (data not shown). The total number of possible synonymous and non-synonymous sites in an individual sequence was between 1,082 and 1,104 with an average of 1,095. The total synonymous-site differences between paired samples were between 8 and 121 (standard error between 3 and 9) with a mean of 65 (Table 3), and the non-synonymous-site differences were between 12 and 129 (standard error between 3 and 12) with a mean of 69 (Table 4). We found that the range of the paired samples K_S (calculated using MEGA 2.1 software) was 0.028–0.410 (standard error between 0.009 and 0.028) with a mean of 0.223, and the K_A range was 0.015–0.161 (standard error between 0.006 and 0.015) with a mean of 0.086 (data not shown). The K_S values are significantly higher than the K_A values ($P < 0.0005$, according to Student's t-test). Table 5 shows the K_A/K_S ratios where all the values are within a range of 0.219–0.763, indicating that the α1,3-GT genes are in a direction from negative, purifying selection to neutrality. The ratios between the species that express the active enzyme are around 0.2–0.4 and those of primates, including cebus, orangutan and human but not marmoset, are around 0.7–0.8 irrespective of whether the enzyme is active (cebus) or inactive (orangutan and human). The marmoset α1,3-GT gene shows an intermediate type: 0.273 with that of cebus and about 0.7–0.8 with that of orangutan and human (Table 5).

Phylogenetic trees of the α1,3-GT genes

To analyze the evolutionary distance among α1,3-GT genes of feline, murine, bovine, porcine,

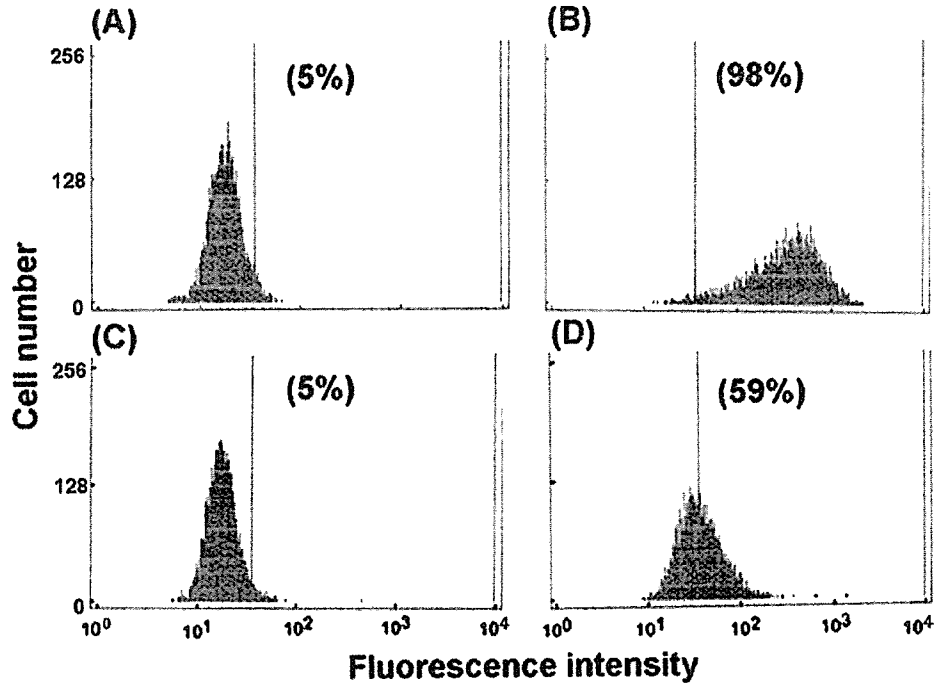

Fig. 2. Detection of α-galactosyl epitope expression. The pcDNA3 vector-transfected HOS/HTLV-I and the feline α1,3-GT plasmid-transfected HOS/HTLV-I cells were initially treated with buffer (**A** and **B**) alone or α-galactosidase (**C** and **D**). The cells were then processed for FCM (as described in Fig. 1) and examined for the expression of α-galactosyl epitope on the cell surface.

cebus and marmoset origins and the α1,3-GT pseudogenes in orangutan and human species, we constructed phylogenetic trees for these α1,3-GT genes and pseudogenes by the N–J method (Saitou and Nei, '87) using the total coding nucleotide sequences (date not shown) and the amino acid sequences (Fig. 4). When the feline α1,3-GT nucleotide sequence was aligned with the other α1,3-GT nucleotide sequences and a phylogenetic tree was made with Poisson correction, it was closely related with the other mammalian α1,3-GT nucleotide sequences. The phylogenetic tree showed that the feline α1,3-GT gene clustered with all other mammalian α1,3-GT genes, especially with the porcine and bovine genes, with a bootstrap support of 93% (date not shown).

The phylogenetic tree constructed using the deduced amino acid sequences shown in Fig. 4 reveals a markedly similar pattern to that constructed using the nucleotide sequences. We also aligned 1–83 and 84–370 amino acid sequences of the feline α1,3-GT with all other α1,3-GT amino acid sequences to make two other phylogenetic trees (data not shown). Both of the phylogenetic trees show almost the same pattern as shown in Fig. 4.

DISCUSSION

When HOS/HTLV-I human cells were transfected with the cDNA encoding the feline α1, 3-GT, they became positive for the expression of α-galactosyl epitopes. In addition, α-galactosidase treatment of HOS/HTLV-I cells transfected with the feline α1,3-GT led to specific reduction of α-galactosyl epitope expression (Fig. 2) as detected by staining with FITC/BS-IB_4. The enzymatic removal of α-galactosyl epitopes was, however, incomplete, probably because the reaction was performed at sub-optimal pH to preserve the cell viability as described by Bracy et al. ('98). Thus, newly cloned human cells showed the stable expression of the feline α1,3-GT (Fig. 1), which catalyzes the addition of α-galactosyl epitopes to existing carbohydrate side chains.

According to the general topology of glycosyltransferases (Paulson and Colley, '89; Joziasse et al., '92), it has been reported that there are three domains in the sequences of glycosyltransferases: a cytoplasmic domain, a transmembrane domain and a luminal domain. Henion et al. ('94) have shown that the 67 amino acids from positions

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Feline     MNVKGRVVLSMLVVSTVIVVFWEYINSPEGSFLWIYHSKNPEVGDSSTQKGWWFPSWFNN : 60
Murine     .....K.I.L..I....V......V...D........T.I....ENRW..D.......K. : 60
Bovine     .....K.I.................H.....LF..NP.R.....G..I.....L.R.... : 60
Porcine    ............L....M.............LF...Q.......-..A.R.......... : 59
Marmoset   .....K.I.....................................D...A..D....G.... : 60
Cebus      .....K.I.....................................D.-.A.......G.... : 59
Orangutan  .....K.I............I......T................D....A.....L..... : 60
Human      .....K.I..............F...T................D...A......L..... : 60

Feline     RTHSYPEEEAVD----EGDEQRKENSE--ELQLSDWFNPQKRPDVVTVTEWKAPVVWEGT :114
Murine     G....Q.DNVEG-----RR.KGRNGDRIE.P..W.....KN....L...P....I..... :115
Bovine     ---G.H..DGDI----NEEKEQRNED.-SK.K.......F...E...M.K.......... :112
Porcine    G....H...DAI----GNEKEQRKEDNRG..P.V.....E...E...I.R.......... :115
Marmoset   GI.N.QQ..EDTDKEKGRE.EQ.KEDDTT..R.W.....K...E.M...Q.......... :120
Cebus      GI.N.QQ..EDIDKEKGRE.EQRKEDDTT....W.....K...E.....K.......... :119
Orangutan  GI.N.QQR.EDIDKEKGRE.-QRKENDTT..R.W.....K...K.....R.......... :119
Human      GI.N.QQG.EDIDKEKGRE.-QRKENDTT..R.W.....K.H.E.....R.......... :119

Feline     YNKAILENYYARQKITVGLTVFAVGRYIEHYLEEFLISANRYFMVGHKVIFYIMVDDVSK :174
Murine     .DT.L..K...T..L..........K.......D..E..DM......R....V.I..T.R :175
Bovine     ..R.V.D....K.............................KH.....P...........R :172
Porcine    ..R.V.D....K.............................T...............I.R :175
Marmoset   ..........K...........I...........VT..............V....... :180
Cebus      ..........K...........I...........VT..............V....... :179
Orangutan  F.....G....K.......M...I...NG......IT.......................... :179
Human      F.....G....K.....R.M...I...ND......IT.......................... :179

Feline     MPLIELGPLRSFKVFEIKPEKRWQDISMMRMKIIGEHIVAHIQHEVDFLFCMDVDQVFQD :234
Murine     ..VVH.N..H.LQ....RS.............T.....L.......................... :235
Bovine     ..............K.................T.............................. :232
Porcine    ..................S.............T.....L.....................N :235
Marmoset   A.F.............V...............T.....L.......................... :240
Cebus      V.F.............V...............T.....L.......................... :239
Orangutan  V.F......H......V...............T....L.......................... :239
Human      L.F......H...M..V...............T....L.......................... :239

Feline     SFGVETLGQSVAQLQAWWYKADPDEFTYERRKESAAYIPFGEGDFYYHAAIFGGTPTQVL :294
Murine     N........L...........S.EK......EL.........................HI. :295
Bovine     K.......E.............ND.................................... :292
Porcine    N....................H.....................Q.................. :295
Marmoset   H.......................D.................Q..............I... :300
Cebus      H.......................D......R.........Q........V.....I... :299
Orangutan  H..............R......D..*...E.........Q.-.................. :298
Human      H..............-.R.....YD..*..W....G.....Q.-.......S....I... :297

Feline     NITQECFKGILQDKKNDIEAEWHDESHLNKYFLLNKPTKILSPEYCWDYHIGLPSDIKIV :354
Murine     .L.R...........H....Q............F...............Q........S. :355
Bovine     ...........K........Q.....................................A...L. :352
Porcine    ..............E.....................................MSV..R.. :355
Marmoset   ...........L.........................S.....................T. :360
Cebus      ...........L.........................S.....................T. :359
Orangutan  ...R...N...L.....V..................S....LK..............T. :358
Human      ...........L........K..............S....LK..............T. :357

Feline     KISWQTKEYNLVRNNI :370
Murine     .VA............V :371
Bovine     .M........V....V :368
Porcine    ..A..K.......... :371
Marmoset   .L...........K.V :376
Cebus      .L.............. :375
Orangutan  .R.R...........V :374
Human      .*............V :373
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Fig. 3. Alignment of deduced amino acid sequences of different α1,3-GT genes. The amino acid sequences of the feline, porcine, murine, bovine, cebus and marmoset α1,3-GT genes and human and orangutan α1,3-GT pseudogenes are aligned using CLUSTAL W algorithm. Numbers at the right side indicate amino acid positions. Dots (.) represent amino acids identical to those in the feline gene sequence. Amino acid deletions in each gene are indicated by dash marks (-). In the human sequence, the star marks (*) indicate premature stop codons.

TABLE 2. Nucleotide and amino acid similarity between the feline and other α1,3-GT genes

Species	Nucleotide similarity (%)	Amino acid sequence				
		1–83 domain		84–370 domain		Total
		Similarity (%)	Gap	Similarity (%)	Gap	Similarity (%)
Murine	81	62	1[1]	82	0	77
Bovine	88	65	3	90	0	85
Porcine	90	72	1	91	0	87
Marmoset	89	72	0	91	0	87
Cebus	89	72	1	91	0	87
Orangutan	88	70	1	86	1	83
Human	88	70	1	86	2	82

The total coding sequences of the α1,3-GT genes were aligned, including gaps. Identical nucleotides and amino acids at each position, excluding gaps, were counted and a similarity rate (%) was calculated between the feline α1,3-GT gene and each α1,3-GT gene or pseudogene.
[1]Number of amino acid gaps placed when compared with the 1–83 or 84–370 domains of the feline α1,3-GT gene.

TABLE 3. Total number of synonymous differences between paired species among eight different α1,3-GTs

Species	Species							
	Feline	Murine	Bovine	Porcine	Marmoset	Cebus	Orangutan	Human
Feline	—							
Murine	107	—						
Bovine	79	120	—					
Porcine	64	113	61	—				
Marmoset	76	95	74	63	—			
Cebus	71	94	77	61	16	—		
Orangutan	71	87	68	56	17	15	—	
Human	72	91	73	59	21	17	8	—

Total possible synonymous sites were between 287 and 296 with an average of 292.

TABLE 4. Total number of non-synonymous differences between paired species among eight different α1,3-GTs

Species	Species							
	Feline	Murine	Bovine	Porcine	Marmoset	Cebus	Orangutan	Human
Feline	—							
Murine	100	—						
Bovine	62	123	—					
Porcine	51	110	65	—				
Marmoset	48	107	68	64	—			
Cebus	43	106	63	60	12	—		
Orangutan	60	123	83	79	37	34	—	
Human	60	129	83	79	40	36	18	—

Total possible non-synonymous sites were between 795 and 810 with an average of 803.

23 to 89 in the marmoset α1,3-GT gene, which they called a stem region, have little effect on enzymatic activity, but the sequence between 90 and 376 can show an almost full catalytic activity. The presence of stop codons in human and orangutan α1,3-GT genes at the site corresponding to the 268th amino acid of the marmoset gene (Fig. 3) will lead to the loss of about 100 amino acids at the C-terminus. This loss is expected to be sufficient to lose the entire catalytic activity