Expression of the Human Poliovirus Receptor/CD155 Gene Is Activated by Sonic Hedgehog

David J. Solecki†‡§, Matthias Gromeier‡¶, Steffen Mueller†, Günter Bernhardt**‡‡, and Eckard Wimmer‡

From the †Department of Molecular Genetics and Microbiology, School of Medicine, State University of New York at Stony Brook, Stony Brook, New York 11794 and **Max-Delbrück-Centrum für Molekulare Medizin, Robert-Rössle-Strasse 10, 13092 Berlin, Germany

The human poliovirus receptor/CD155 is a transmembrane glycoprotein belonging to the immunoglobulin superfamily. The ectodomain of CD155 mediates cell attachment to the extracellular matrix molecule vitronectin, while its intracellular domain interacts with the dynein light chain Tctex-1. CD155 is a primate-restricted gene that is expressed during development in mesenchymal tissues and ventrally derived structures within the CNS. Its function in adults is as yet unknown, but significantly, CD155 is aberrantly expressed in neuroectodermal tumors. We show that the expression of CD155 mRNA is up-regulated when human Ntera2 cells are treated with purified Sonic hedgehog (Shh) protein. Reporter gene expression driven by the CD155 core promoter is activated by Shh in transient co-transfection assays. Analysis of the CD155 core promoter indicates that an intact GLI binding site is required for Shh activation. In addition, overexpression of GLI1 or GLI3 potentially activates reporter gene expression driven by the CD155 core promoter. These data identify the CD155 gene as a transcriptional target of Shh, a finding that has significance for the normal function of CD155 during development and the expression of CD155 in neuroectodermal tumors.

The human poliovirus receptor/CD155 is a type I transmembrane glycoprotein belonging to the immunoglobulin superfamily (Refs. 1 and 2; for review, see Ref. 3). The CD155 gene is the founding member of the new CD155/nectin subclass of genes within the immunoglobulin superfamily that share a common V-C2-C2 extracellular Ig domain signature, which also includes nectin-1, -2, -3, -4, and Tage4 (4–8). CD155 mediates cell adhesion to the extracellular matrix molecule vitronectin (9). Its intracellular C-terminal domain has affinity to Tctex-1, a subunit of the dynein motor complex (10). The nectins, on the other hand, possess homotypic and heterotypic cell adhesion activities (8, 11–15). Intriguingly CD155, nectin-1, -2, and Tage4 serve as receptors for human viruses. CD155 is the only known receptor for poliovirus (1, 16), while the nectins are receptors for α-herpesviruses (17–19). More recently CD155 has been revealed as a tumor antigen and a potential target for therapeutic intervention as its expression is up-regulated in neuroectodermal cancers, including glioblastoma multiforme, medulloblastoma, and colorectal carcinoma (20, 21).

We have examined the expression and transcriptional regulation of the CD155 gene to elucidate the basic biology of its gene product (22–24). Our preliminary studies have revealed that CD155 is expressed during embryonic development with peak levels that occur during midgestation and then decline (25). Expression is observed in mesenchymal structures like the notochord and ventrally derived structures of the developing central nervous system (CNS)1 such as the floor plate, motor neurons of the ventral neural tube, and retinal ganglion layer of the retina. The related nectin-1 (PRR1) gene has been mapped as a locus of inherited midline dysraphism syndromes in humans (26). Analyses of transcriptional regulation of CD155 expression demonstrated activator protein-2 (AP-2) and nuclear respiratory factor-1 (NRF-1) to be potent regulators of CD155 transcription (23, 24). During CNS development, these transcription factors are expressed in some of the locations of CD155 expression, such as neural tube and retina, suggesting a role for these factors in directing developmental CD155 expression (27–29).

AP-2 and NRF-1 are not expressed in ventral midline structures during embryogenesis (27–29), an observation suggesting that our understanding of the factors contributing toward expression of CD155 remains incomplete. The secreted morphogen Sonic hedgehog (Shh) plays an essential role in patterning many structures during development, including the notochord and ventral CNS, the developing limb, lung, and foregut (30–33). The most well characterized location for Shh action is the anterior neural tube, associated with notochord, floor plate, and the motoneuronal system. Secreted Shh from the notochord induces floor plate, which in turn becomes a source of Shh that patterns many ventral neuron types along the entire anterior-posterior axis of the developing CNS (31). Another location of Shh action is the developing optic system (34, 35). Shh is expressed in the retinal ganglion layer and regulates patterning and cell number in the developing retina (34, 35).

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† A member of the graduate program in Molecular and Cellular Biology, State University of New York at Stony Brook and recipient of a grant from the Deutscher Akademischer Austauschdienst (DAAD). To whom inquiries should be addressed: Laboratory of Developmental Neurobiology, The Rockefeller University, 1280 York Ave., New York, NY 10021. E-mail: solecki@mail.rockefeller.edu.

‡ Recipient of a Burroughs Wellcome Career Award. Current address: Dept. of Molecular Genetics and Microbiology, Duke University Medical Center, Durham, NC 27710.

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1 The abbreviations used are: CNS, central nervous system; Shh, Sonic hedgehog; AP-2, activator protein-2; NRF-1, nuclear respiratory factor-1; RT, reverse transcription; E13.5, embryonic day 13.5; FP, footprinted region.
Moreover Shh is a potent mitogen for neuronal precursors (36, 37). Interestingly Shh signaling has been implicated in the oncogenesis of neuroectodermal tumors because mutations in the Shh receptor Patched are observed in medulloblastoma and basal cell carcinomas (38–41). Indeed activation of the Shh signaling cascade, either by mutation or overexpression of activated signaling components, has been shown to cause medulloblastomas and basal cell carcinomas in mice (42–44).

The mechanism(s) of the morphogenic activity of Shh is currently under investigation (45, 46). Available evidence suggests transmission of a Shh signal to occur by the diffusible 19-kDa Shh N-terminal fragment that is autoproteolytically cleaved from the full-length Shh protein by the action of the Shh C terminus. The secreted Shh N-terminal fragment binds to the Patched-Smoothened receptor complex that leads to transduction of the Shh signal. Shh receptor activation induces GLI proto-oncogene transcription factors, which then bind to and activate the transcription of Shh-responsive genes (45, 46).

Since Shh is involved in the morphogenesis of embryonic structures identified to harbor CD155 expression, we tested whether the CD155 gene is a target of Shh signaling. Here we report the CD155 gene to be transcriptionally activated when human Ntera-2 cells were treated with recombinant Shh protein. Transient overexpression of Shh activated reporter gene expression driven by the CD155 core promoter. Up-regulation of reporter expression was dependent on an intact GLI binding site within the CD155 core promoter. According to their observed function as downstream effectors of the Shh signal, GLI proto-oncogene transcription factors (Gli1 and Gli3) strongly activated the CD155 core promoter.

MATERIALS AND METHODS

Cell Culture—C3H10 T1/2 (mouse embryo fibroblast, ATCC) and Ntera-2 clone D1 (tumor carcinoma, ATCC) cell lines were grown in Dulbecco’s modified Eagle’s medium, 10% fetal bovine serum.

Antibodies—A rabbit polyclonal antiserum, NAEZ-8, was raised against a recombinant protein encompassing the extracellular domain of human CD155 fused to a hexahistidine tag. The protein was expressed in HEK-293 cells and purified to homogeneity from culture supernatants. Mouse monoclonal antibody 5E1 against the N-terminal peptide of Shh was obtained from the Developmental Studies Hybridoma Bank.

Shh Induction Assay and Detection of CD155, Gli1, or β-Actin mRNA—1 × 105 Ntera-2 clone D1 cells were seeded into 10-cm dishes. 18 h after passage, the serum-containing medium that was used to seed the cells was exchanged for serum-free medium. After 12 h, purified Shh-N protein (palmitoylated Shh-N, a kind gift of Phil Beachy, Johns Hopkins University, Baltimore, MD) was then added to the medium to a final concentration of 5 nM (~150 ng/ml) and incubated for 18 h. Total mRNA was then isolated from the untreated and untreated cultures. RT-PCR was then used to analyze the levels of CD155, Gli1, and β-actin RNA within these samples. 10 μg of total RNA was used as template for reverse transcription using Superscript II (Invitrogen) primed with random hexamers, and the resulting first-strand cDNA was amplified in parallel using the following primers: cd155 5’, 5’-cgagcatctctggtgactctgctgctg-3’; cd155 3’, 5’-gcttgagttggtgcatcactgt-3’; Gli1 5’, 5’-attgcccacagctgatcactctggtc-3’; Gli1 3’, 5’-cttcatgctgtactgaggg-3’. The cycling parameters for amplification were 95 °C for 30 s, 55 °C for 30 s, and 72 °C for 1 min for 30 cycles. The PCR products were then run on a 1% agarose gel and transferred to nitrocellulose membranes, and southern hybridization with radiolabeled probes was used to detect the CD155-, Gli1-, or β-actin-specific RT-PCR products.

CD155 Reporter Assays—Transient transfections were carried out in the C3H10 T1/2 mouse fibroblast cell line using FuGENE 6 reagent (Roche Molecular Biochemicals) according to the manufacturer’s instructions. Each transfection mixture contained 250 ng of the wild type CD155 core promoter-BgIII (see Scolnick et al. Refs. 22–24) or AGI reporter plasmids and 5 ng of the pcDNA3-Shh, pcDNA3-Gli1, or pcDNA3-Gli3 expression vectors. Co-transfections were filled in with empty pcDNA3 so that a total of 250 ng of pcDNA3 backbone plasmid would be constant for each transfection. Basal reporter activity was determined by co-transfecting empty pcDNA3 vector alone. 18 h post-transfection cells were harvested, and luciferase activity in the lysates of transfected cells was measured using Luciferase Assay Reagent (Promega).

Immunofluorescence—CD155g21 (47) E13.5 mouse embryos were fixed for 2 h in 4% paraformaldehyde before cryoprotection in OCT cryoprotectant (Tissue-Tek). Frozen sections were collected on poly-l-lysine-coated slides, air dried, and postfixed in cold 1:1 methanol/acetic acid for 1 h at ~20 °C. For CD155/Shh-N double labeling sections were blocked with M.O.M. blocking reagent (Vector Laboratories) followed by overnight incubation at 4 °C with a 1:500 dilution of CD155 antibody NAEZ-8 and 1:2 dilution of hybridoma supernatant 5E1 in M.O.M. diluent (Vector Laboratories). After 1 h of washing with phosphate-buffered saline the sections were incubated with a 1:200 dilution of Alexa-488 conjugated anti-rabbit (Molecular Probes) and a 1:500 dilution of Cy3-conjugated anti-mouse (Jackson Immuno Research) secondary antibodies for 1 h at 37 °C. The sections were washed extensively with phosphate-buffered saline and mounted with Immuno Mount (Shandon, Pittsburgh, PA). CD155 single labeling was essentially done as above except that blocking and antibody dilutions were done in phosphate-buffered saline containing 2% normal goat serum instead of M.O.M. blocking reagent. Images were acquired on a Zeiss Axiosplan II fluorescence microscope equipped with a model SP401 camera (Diagnostic Instruments Inc.) and processed with Adobe Photoshop software.

RESULTS

CD155 Promoter Activity during Embryogenesis in Transgenic Mice—We have recently constructed CD155 promoter-LacZ transgenic mice using a 3.0-kb CD155 core promoter (Fig. LA) to drive the reporter gene (25). Histochemical examination of β-galactosidase activity in embryos harboring the CD155 promoter-LacZ transgene has revealed that the CD155 promoter possesses elements that direct reporter gene expression in a profile similar to the endogenous expression of CD155. β-Galactosidase activity was observed in midline structures, i.e. notochord, floor plate, and presumptive motor neurons of the anterior horn along the anterior-posterior axis of the transgenic embryos. In addition, expression was seen in the developing retina, optic chiasm, and optic nerve.

To expand our studies of CD155 expression during embryogenesis we have also examined CD155 protein expression in CD155 transgenic mice. These mice possess the entire CD155 gene, are susceptible to poliovirus infection, and suffer a syn-
drome very similar to human poliomyelitis suggesting that CD155 is expressed in the appropriate locations. Indeed CD155 protein in embryos of CD155tg mice (ICR-PVRTg21, Ref. 47) is detectable in a profile similar to that in the CD155 promoter-LacZ transgenic mouse embryos. Expression was observed in the floor plate, notochord, and sclerotome (Fig 2A) as well as the optic nerve and chiasm (not shown). Particularly the expression pattern of CD155 within the floor plate matched that of Shh-N (Fig. 2, A–C). We furthermore detected CD155 protein expression in the mesenchyme surrounding the branching primordial tubules of the lung epithelium (Fig. 3, B and C) as well as the cartilage primordium of developing ribs (Fig. 3D). Both tissues are known regulatory targets of the hedgehog signaling cascade (32). It is particularly noteworthy that CD155 was mostly concentrated in the mesenchyme surrounding the more distal portions of the tubules precisely where Gli1 is found and where the highest level of Shh in the adjacent lung epithelium has been reported (32, 48).

**Shh Activates Transcription of the CD155 Gene**—The fact that Shh acts as a global regulator of gene expression in structures associated with CD155 expression led us to test whether Shh could directly modulate the activation of the CD155 gene. For these experiments, we treated undifferentiated human Ntera-2 clone D1 cells with 5 nM Shh-Np protein. Undifferentiated Ntera-2 cells possess a primitive neuroepithelial cell phenotype and are sensitive to many signaling pathways that modulate the differentiation and proliferation of neuronal precursor cells (49, 50). Based on expressed sequence tag data base searches and RT-PCR experiments, Ntera-2 cells express the Shh receptors Patched and Smoothened and the GLI zinc finger transcription factors required for transduction of a Shh signal (data not shown). Total RNA was isolated from treated and untreated Ntera-2 cells, reverse-transcribed with random hexamers, and then amplified with primer sets specific for mRNAs of CD155, the Gli1 transcription factor (a gene known to be activated strongly by Shh), and β-actin (an internal control for RNA loading). Whereas RT-PCR products corresponding to CD155 and Gli1 message could barely be demonstrated in control cultures, abundant β-actin message was readily detected (Fig. 4). In contrast, treatment of Ntera-2 cells with 5 nM Shh-Np produced an increase in both of the CD155- and Gli1-specific transcript RNAs, whereas the β-actin levels remained stable. Gli1 has been demonstrated to be a primary target of the Shh signaling cascade. Our observations of an increase of the CD155 RT-PCR product in the presence of Shh suggested that the CD155 gene, like Gli1, is a transcriptional target of the Shh signaling cascade.

**The CD155 Core Promoter Is Activated by Shh Signaling**—The results of our Shh induction assay provided qualitative evidence that CD155 mRNA is increased by the addition of Shh protein to Ntera-2 cultures, suggesting that CD155 transcription may be activated by Shh. We next sought to determine whether the CD155 promoter could be activated by Shh signaling. Moreover we designed experiments to map the region(s) of the promoter that would convey responsiveness to Shh. Examination of the CD155 promoter revealed three regions with matching GLI consensus binding (51) sites within the 3.0-kb

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**Fig. 2.** CD155 and Shh-N colocalize to the floor plate of CD155tg mouse embryos. Transverse thoracic sections of E13.5 embryos were double labeled for CD155 and Shh-N. A, CD155 is expressed in floor plate, notochord, and sclerotome. B, Shh localization to the floor plate. C, overlay of A and B reveals extensive overlap of CD155 and Shh-N expression patterns in the floor plate. D, control section incubated with preimmune serum and an unrelated mouse IgG hybridoma supernatant. Bars, 100 μm.

**Fig. 3.** CD155 expression in mouse embryonic lung mesenchyme and developing ribs. A, phase contrast image of a transverse section through E13.5 lung. B, the same section stained with CD155specific antiseraum. CD155 is concentrated in the mesenchyme surrounding the distal portion of branching primordial tubules of the developing lung epithelium. C, a higher magnification view of a lung tubule depicted in B. D, CD155 is highly expressed in the cartilage primordia of developing ribs. E, an adjacent control section incubated with preimmune serum shows no nonspecific staining in primordial rib. B, C, and D, CD155 expression was analyzed by indirect immunofluorescence using CD155-specific antiseraum NAEZ-8 (1:500) in combination with an Alexa488-conjugated anti-rabbit secondary antibody (1: 200). Fluorescence was visualized under epifluorescence on a Zeiss Axioplan II microscope equipped with a fluorescein isothiocyanate filter set. Bars, 100 μm.

**Fig. 4.** Expression of CD155 core is activated by Shh. Ntera-2 cells were treated with 5 nM Shh-Np protein. After a 24-h incubation total RNA was isolated, and CD155, Gli1, and β-actin messages were analyzed by RT-PCR. Both the CD155 and Gli1 mRNA are activated by Shh, while the β-actin internal control remains unaffected.
The CD155 core promoter is activated by Shh and GLI factors through the GLI binding motif in FPIII. A, effect of co-transfection of a full-length Shh expression vector on the promoter activity of the wild type and a ΔGLI mutant BE promoter construct in the C3H10 T1/2 cell line. Cells were seeded in six-well tissue culture plates and were transfected with FuGENE 6 with the BE or ΔGLI promoter construct and pcDNA3-Shh. Transfections were filled in with pcDNA3 to keep the amount of expression vector backbone in each reaction at a constant level for all experiments. Transfected cells were harvested 18 h post-transfection, and the luciferase activity contained within the cytoplasmic extract of transfected cells was determined using the Luciferase Reporter System (Promega). The activity of the promoter construct co-transfected with only pcDNA3 was set to 100% (control promoter activity), and the level of activation caused by co-transfected of pcDNA3-Shh is expressed relative to that 100%. Results are the mean ± S.D. of triplicate transfections. The average Renilla luciferase corrected relative light unit values of these transfections were 1200 (BE) and 1300 (ΔGLI). B, effect of co-transfection of GLI transcription factor expression vectors on the promoter activity of the wild type and a ΔGLI mutant BE promoter construct in the C3H10 T1/2 cell line. Cells were seeded in six-well tissue culture plates and were transfected with FuGENE 6 with the BE or ΔGLI promoter construct and pcDNA33-Gli1 or -Gli3. Transfections, harvest, and the luciferase assay were carried out as described in A. The activity of the promoter construct co-transfected with only pcDNA3 was set to 100% (control promoter activity), and the level of activation caused by co-transfected of pcDNA33-Gli1 or -Gli3 is expressed relative to that 100%. Results are the mean ± S.D. of triplicate transfections. The average Renilla luciferase corrected relative light unit values of these transfections were 1200 (BE) and 1300 (ΔGLI).

DISCUSSION

Temporospatial expression patterns for many cell adhesion molecules of the immunoglobulin superfamily are consistent with functions during embryonic development. We have described activity of the CD155 promoter and expression of CD155 protein in anterior midline structures of the developing human CNS (25). Similarly, in CD155tg mouse embryos, CD155 can be detected in the notochord, ventral neural tube, optic nerve/chiasm, and cartilage primordia such as the rib and
sclerotome as well as the mesenchyme surrounding the branching primordial tubules of the developing lung (see Figs. 2 and 3). Shh, an important morphogen, is expressed in many of the same locations as CD155 during development (Refs. 30–33 and 48, and See Fig. 2). We tested the possibility that the CD155 gene may be a transcriptional target of the Shh signaling cascade. The CD155 core promoter harbors a potential GLI binding motif (Fig. 5). Not surprisingly co-transfection of a Shh expression vector and that this activity of Shh signaling. Importantly this hypothesis is supported by data indicating that the CD155 core promoter is activated by co-transfection of a Shh expression vector and that this activity required an intact GLI binding motif (Fig. 5). Not surprisingly GLI proto-oncogene transcription factors themselves (Gli1 and Gli2) directly activated the CD155 core promoter (Fig. 5).

The observed role of Shh and GLI transcription factors in the regulation of expression of CD155 is consistent with their association with structures associated with the developing embryo (31). Our previous studies have dissected the cis-acting elements required for basal activity of the CD155 core promoter and identified their interactions with AP-2 and NRF-1 transcription factors (22–24). The GLI binding motif located within the boundaries of FPIII differs from the NRF-1 and AP-2 consens binding sites in that mutation of this motif had little effect on basal promoter activity (24). This suggests that this cis-element may act as a Shh-dependent enhancer within the CD155 core promoter. Shh-dependent activation of the CD155 promoter may contribute to the observed expression profile of CD155 within embryonic structures patterned by Shh.

Shh activation of CD155 expression may be highly relevant for the overexpression of CD155 in cancers like medulloblastoma or glioblastoma. A peak of CD155 expression was observed during midgestation of human and transgenic mouse embryos (Ref. 25, and see Figs. 2 and 3). Interestingly up-regulation of CD155 expression is observed in neuroectodermal malignancy (e.g. medulloblastoma or glioblastoma), an observation suggesting that gene regulatory pathways exist in these tumors that reactivates CD155 expression (20). Recently both Shh and the GLI transcription factors have been implicated in the oncogenesis of neuroectodermal and cutaneous cancers (for review, see Ref. 56). Loss-of-function mutations of the Shh receptor Patched are found in spontaneous and familial forms of medulloblastoma (40, 41). Indeed loss of one Patched allele reportedly led to medulloblastoma-like lesions in the cerebellum of mice (42). Human Gli1 was first identified because of its association with glioblastoma (57), and the Gli1 gene has subsequently been localized near a hotspot of gene duplication in these tumors (58). Up-regulation of Gli1 expression is commonly observed in human medulloblastomas (56, 59) and the medulloblastoma-like lesions of germ line manipulated mice lacking one Patched allele (42). Up-regulation of GLI genes may be an important determinant in carcinogenesis as constitutive overexpression of Gli1 or Gli2 in skin leads to spontaneous basal cell carcinomas (43, 44). In this study, we show that CD155 expression is activated by Shh signaling and that the CD155 core promoter is strongly activated by Gli1 and Gli3. Based on the data presented here, Shh and GLI signaling may be the critical gene regulatory pathway activating CD155 expression in medulloblastoma and glioblastoma. This hypothesis is currently being tested in our laboratory.

CD155 has been reported to mediate cell adhesion to the extracellular matrix by a specific interaction with vitronectin (9). The pattern of vitronectin expression during embryonic development overlaps that of CD155, including the notochord, floor plate, and ventral neural tube (60, 61). It is interesting to note that the vitronectin gene also is a Shh target and that its product binds directly to Shh thereby modifying cellular responses to Shh (62). The physiological role of the CD155/vitronectin/extracellular matrix interaction is unclear in this context. Given the role of vitronectin in modulating Shh responses and the fact that CD155 and vitronectin are both expressed in locations of Shh action, it is tempting to speculate that CD155 may not simply represent a Shh target gene. It may be a constituent of the cellular machinery that modulates Shh action. Interestingly nectin-1, one of the nectin molecules related to CD155, is specifically expressed in the floor plate.3 Examination of the upstream sequence of the nectin-1 gene deposited in the Human Genome Database has revealed the presence of multiple GLI binding motifs suggesting that other nectin-related molecule besides CD155 may be expressed in the floor plate and may be regulated by Shh signaling.

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REFERENCES

1. Mendelsohn, C. L., Wimmer, E., and Racianni, V. R. (1989) Cell 56, 855–865
2. Koike, S., Horie, H., Ise, I., Ouchita, A., Yoshida, M., Izuka, N., Takeuchi, K., Takesami, T., and Nomoto, A. (1990) EMBO J. 9, 3217–3224
3. Wimmer, E., Harber, J. J., Bibb, J. A., Gromeier, M., Lu, H.-H., and Bernhardt, G. (1994) in Cellular Receptors for Animal Viruses (Wimmer, E., ed) pp. 101–127, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY
4. Chadehoun, C., LeMoulic, B., and Denis, M. G. (1994) J. Biol. Chem. 269, 15601–15605
5. Eberle, P., Dubreuil, P., Mattei, M. G., Devillard, E., and Lopez, M. (1995) Gene (Amst.) 159, 267–272
6. Lopez, M., Eberle, F., Mattei, M. G., Gabert, J., Biry, F., Bardin, F., Marce, C., and Dubreuil, P. (1995) Gene (Amst.) 159, 261–265
7. Reyon, N., Borg, J. P., Lecocq, E., Adalouverie, J., Campelladelli-Fiume, G., Dubreuil, P., and Lopez, M. (2000) Gene (Amst.) 255, 347–355
8. Reyon, N., Fabre, S., Lecocq, E., Dubreuil, P., and Lopez, M. (2001) J. Biol. Chem. 276, 43205–43215
9. Lange, R., Peng, X., Wimmer, E., Lipp, M., and Bernhardt, G. (2001) J. Biol. Chem. 276, 218–227
10. Mueller, S., Caou, X., Welker, R., and Wimmer, E. (2002) J. Biol. Chem. 277, 7897–7904
11. Aoki, J., Koike, S., Asoh, H., Ise, I., Sawa, H., Tanaka, T., Miyasaki, M., and Nomoto, A. (1997) Exp. Cell Res. 235, 374–384
12. Lopez, M., Aoubala, M., Jordier, F., Isnardon, D., Gomez, S., and Dubreuil, P. (1998) Blood 92, 4602–4611
13. Miyahara, M., Nakahishin, H., Takahashi, K., Satoh-Horikawa, K., Tachibana, K., and Takai, Y. (2000) J. Biol. Chem. 275, 613–618
14. Takahashi, K., Nakahishin, H., Miyahara, M., Mondeni, K., Satoh, K., Satoh, A., Nishikawa, H., Aoki, J., Nomoto, A., Mizuguchi, A., and Takai, Y. (1999) J. Cell Biol. 145, 539–544
15. Tachibana, K., Nakahishin, H., Mondeni, K., Ozaki, K., Ikeda, W., Yamamoto, Y., Nagauchi, A., Tsuchita, K., and Takai, Y. (2000) J. Cell Biol. 150, 1161–1176
16. Bernhardt, G., Bibb, J. A., Bradley, J., and Wimmer, E. (1994) Virology 199, 105–113
17. Cocchi, F., Menotti, L., Miranda, P., Leproti, M., and Campedelli-Fiume, G. (1998) J. Virol. 72, 9902–10002
18. Geraghty, R. J., Krummenacher, C., Cohen, G. H., Eisenberg, R. J., and Spear, P. G. (1998) Science 280, 1618–1620
19. Baubry, B., Geraghty, R. J., Masson, D., Lustenberg, P., Spear, P. G., and Denis, M. G. (2001) Gene (Amst.) 265, 185–194
20. Gromeier, M., Lachmann, S., Rosenfeld, M. R., Gutin, P. H., and Wimmer, E. (2000) Proc. Natl. Acad. Sci. U. S. A. 97, 6803–6808
21. Masson, D., Jarry, A., Baubry, B., Lachmann, S., Laboisse, C., Lustenberg, P., and Denis, M. G. (2001) Gut 49, 236–240
22. Solecki, D., Schwartz, S., Wimmer, E., Lipp, M., and Bernhardt, G. (1997) J. Biol. Chem. 272, 5579–5586
23. Solecki, D., Bernhardt, G., Lipp, M., and Wimmer, E. (2000) J. Biol. Chem. 275, 12453–12462

3 S. Mueller, J. Zhan, and E. Wimmer, unpublished observations.
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