BRIEF REPORT

Long-Term Control of HIV by *CCR5* Delta32/Delta32 Stem-Cell Transplantation

Gero Hütter, M.D., Daniel Nowak, M.D., Maximilian Mossner, B.S., Susanne Ganepola, M.D., Arne Müßig, M.D., Kristina Allers, Ph.D., Thomas Schneider, M.D., Ph.D., Jörg Hofmann, Ph.D., Claudia Kücherer, M.D., Olga Blau, M.D., Igor W. Blau, M.D., Wolf K. Hofmann, M.D., and Eckhard Thiel, M.D.

SUMMARY

Infection with the human immunodeficiency virus type 1 (HIV-1) requires the presence of a CD4 receptor and a chemokine receptor, principally chemokine receptor 5 (CCR5). Homozygosity for a 32-bp deletion in the *CCR5* allele provides resistance against HIV-1 acquisition. We transplanted stem cells from a donor who was homozygous for *CCR5* delta32 in a patient with acute myeloid leukemia and HIV-1 infection. The patient remained without viral rebound 20 months after transplantation and discontinuation of antiretroviral therapy. This outcome demonstrates the critical role *CCR5* plays in maintaining HIV-1 infection.

From the Department of Hematology, Oncology, and Transfusion Medicine (G.H., D.N., M.M., S.G., A.M., O.B., I.W.B., W.K.H., E.T.) and the Department of Gastroenterology, Infectious Diseases, and Rheumatology (K.A., T.S.), Campus Benjamin Franklin; and the Institute of Medical Virology, Campus Mitte (J.H.) — all at Charité Universitätsmedizin Berlin; and the Robert Koch Institute (C.K.) — all in Berlin. Address reprint requests to Dr. Hütter at Medical Department III Hematology, Oncology, and Transfusion Medicine, Charité Campus Benjamin Franklin, Hindenburgdamm 30 D-12203 Berlin, Germany, or at gero.huetter@charite.de.

Drs. Hofmann and Thiel contributed equally to this article.

N Engl J Med 2009;360:692-8.
Copyright © 2009 Massachusetts Medical Society.

HIV-1 ENTERS HOST CELLS BY BINDING TO A CD4 RECEPTOR AND THEN interacting with either CCR5 or the CXC chemokine receptor (CXCR4). Homozygosity for a 32-bp deletion (delta32/delta32) in the *CCR5* allele results in an inactive *CCR5* gene product and consequently confers high resistance against HIV-1 acquisition.[1]

Allogeneic stem-cell transplantation from an HLA-matched donor is a feasible option for patients with hematologic neoplasms, but it has not been established as a therapeutic option for patients who are also infected with HIV.[2] Survival of patients with HIV infection has improved considerably since the introduction of highly active antiretroviral therapy (HAART),[3] and as a consequence, successful allogeneic stem-cell transplantation with ongoing HAART was performed in 2000.[4]

In this report, we describe the outcome of allogeneic stem-cell transplantation in a patient with HIV infection and acute myeloid leukemia, using a transplant from an HLA-matched, unrelated donor who was screened for homozygosity for the *CCR5* delta32 deletion.

CASE REPORT

A 40-year-old white man with newly diagnosed acute myeloid leukemia (FAB M4 subtype, with normal cytogenetic features) presented to our hospital. HIV-1 infection had been diagnosed more than 10 years earlier, and the patient had been treated with HAART (600 mg of efavirenz, 200 mg of emtricitabine, and 300 mg of tenofovir per day) for the previous 4 years, during which no illnesses associated with the acquired immunodeficiency syndrome (AIDS) were observed. At the time that acute myeloid

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

leukemia was diagnosed, the patient's CD4 T-cell count was 415 per cubic millimeter, and HIV-1 RNA was not detectable (stage A2 according to classification by the Centers for Disease Control and Prevention). Initial treatment of the acute myeloid leukemia consisted of two courses of induction chemotherapy and one course of consolidation chemotherapy. During the first induction course, severe hepatic toxic effects developed and renal failure occurred. Consequently, HAART was discontinued, leading to a viral rebound (6.9×10^6 copies of HIV-1 RNA per milliliter). The therapy was resumed immediately, before a viral steady state was reached, and 3 months later, HIV-1 RNA was undetectable.

Seven months after presentation, acute myeloid leukemia relapsed, and the patient underwent allogeneic stem-cell transplantation with CD34+ peripheral-blood stem cells from an HLA-identical donor who had been screened for homozygosity for the *CCR5* delta32 allele. The patient provided informed consent for this procedure, and the protocol was approved by the institutional review board. The HLA genotypes of the patient and the donor were identical at the following loci: A*0201; B*0702,3501; Cw*0401,0702; DRB1*0101,1501; and DQB1*0501,0602. The patient underwent a conditioning regimen and received a graft containing 2.3×10^6 CD34+ cells per kilogram of body weight.[5] Prophylaxis against graft-versus-host disease consisted of 0.5 mg of rabbit antithymocyte globulin per kilogram 3 days before transplantation, 2.5 mg per kilogram 2 days before, and 2.5 mg per kilogram 1 day before. The patient received two doses of 2.5 mg of cyclosporine per kilogram intravenously 1 day before the procedure and treatment with mycophenolate mofetil at a dose of 1 g three times per day was started 6 hours after transplantation. HAART was administered until the day before the procedure, and engraftment was achieved 13 days after the procedure. Except for the presence of grade I graft-versus-host disease of the skin, which was treated by adjusting the dosage of cyclosporine, there were no serious infections or toxic effects other than grade I during the first year of follow-up. Acute myeloid leukemia relapsed 332 days after transplantation, and chimerism transiently decreased to 15%. The patient underwent reinduction therapy with cytarabine and gemtuzumab and on day 391 received a second transplant, consisting of 2.1×10^6 CD34+ cells per kilogram, from the same donor, after treatment with a single dose of whole-body irradiation (200 cGy). The second procedure led to a complete remission of the acute myeloid leukemia, which was still in remission at month 20 of follow-up.

METHODS

CCR5 GENOTYPING

Genomic DNA was extracted from heparinized peripheral-blood monocytes obtained from the patient and the prospective donor, with the use of the QIAamp Blood Midi Kit (Qiagen). Screening of donors for the *CCR5* delta32 allele was performed with a genomic polymerase-chain-reaction (PCR) assay, with primers flanking the site of the deletion (forward, 5′CTCCCAGGAATCATCTTTACC3′; reverse, 5′TCATTTCGACACCGAAGCAG3′), resulting in a PCR fragment of 200 bp for the *CCR5* allele and 168 bp for a delta32 deletion. Results were confirmed by allele-specific PCR and by direct sequencing with the use of the BigDye Terminator v1.1 Cycle Sequencing Kit (Applied Biosystems). Sequences were analyzed with the use of Vector NTI ContigExpress software (Invitrogen).

VIRAL-ENVELOPE GENOTYPING

Coreceptor use by HIV-1 was assessed through V3 amino acid sequences of the *env* region for both DNA and RNA. Bulk PCR products were subjected to direct sequencing and determined according to the 11/25 and net charge rules, as described by Delobel et al.[6]

For RNA, the HIV *env* region was sequenced from position 6538 to 6816 and Web position-specific scoring matrix (WebPSSM), and geno2pheno bioinformatic software was used to predict viral coreceptor use. In addition, an ultradeep PCR analysis with parallel sequencing (454-Life-Sciences, Roche) was performed.[7]

CHEMOKINE RECEPTORS AND SURFACE ANTIGENS

Mucosal cells were isolated from 10 rectal-biopsy specimens according to the method of Moos et al.[8] *CCR5* expression was stimulated by phytohemagglutinin (Sigma), and the cells were analyzed by means of flow cytometry with the use of antibodies against CD3, CD4, CD11c, CD163, and CCR5 (BD Biosciences).

CHIMERISM

Standard chimerism analyses were based on the discrimination between donor and recipient alleles

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

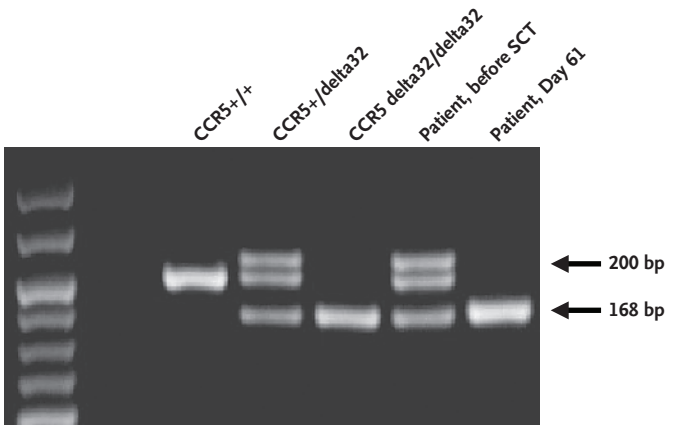

Figure 1. Genotyping of *CCR5* Alleles.

Polymerase-chain-reaction (PCR) assays reveal the genotyping patterns of different *CCR5* alleles and the phenotype of the HIV-1 envelope. Amplification of the homozygous wild-type allele (*CCR5*+/+) results in a single band of 200 bp. The sample that is homozygous for the *CCR5* delta32 allele (*CCR5* delta32/delta32) produces a single band of 168 bp. Before stem-cell transplantation (SCT), the patient had a heterozygous genotype (*CCR5*+/delta32); after transplantation, with ongoing engraftment, the genotype changed to *CCR5* delta32/delta32. Samples containing heterozygous alleles produce both bands, plus an additional third band that may be an artifact arising from secondary structures of PCR products.

on short tandem repeats, with the use of PCR and fluorescence-labeled primers according to the method of Blau et al.[9]

CELLULAR AND HUMORAL IMMUNE RESPONSES

Secretion of interferon-γ by antigen-specific cells was induced according to the method of Ganepola et al.[10] For measurement of T-cell–mediated immune responses, two HLA-A*0201–binding peptides were used: HIV-$1_{476–484}$ (ILKEPVHGV) and cytomegalovirus $(CMV)_{65–73}$ (NLVPMVATV). The presence of antibodies against HIV-1 and HIV type 2 (HIV-2) was determined by means of an enzyme-linked immunoassay and immunoblot assays in accordance with the procedures recommended by the manufacturers (Abbott and Immogenetics).

AMPLIFICATION OF HIV-1 RNA AND DNA

HIV-1 RNA was isolated from plasma and amplified with the use of the Cobas AmpliPrep–TaqMan HIV assay system (Roche). Total DNA was isolated from peripheral-blood monocytes and rectal-biopsy specimens with the use of the QIAamp DNA Blood Mini Kit and the AllPrep DNA/RNA Mini Kit, respectively (both from Qiagen). The *env* and long-terminal-repeat regions were amplified according to the method of Cassol et al. and Drosten et al.[11,12] The sensitivity of the RNA assay was 40 copies per milliliter, and the lower limit of detection for both complementary DNA (cDNA) PCR assays is 5 copies per reaction, with a positivity rate of more than 95%. Each assay contained 2×10^4 to 5×10^4 CD4+ T cells. The successful amplification of 1 μg of cellular DNA extracted from various housekeeping genes (*GAPDH*, *CCR5*, and *CD4*) extracted from 1 μg cellular DNA indicated the suitability of the DNA isolated from the mucosal specimens.

RESULTS

DISTRIBUTION OF CCR5 ALLELES

Genomic DNA from 62 of 80 potential HLA-identical stem-cell donors registered at the German Bone Marrow Donor Center was sequenced in the *CCR5* region. The frequencies of the delta32 allele and the wild-type allele were 0.21 and 0.79, respectively. Only one donor was homozygous for the *CCR5* delta32 deletion in this cohort.

ANALYSIS OF HIV-1 CORECEPTOR PHENOTYPE

Sequence analysis of the patient's viral variants revealed a glycine at position 11 and a glutamic acid at position 25 of the V3 region. The net charge of amino acids was +3. These results indicated CCR5 coreceptor use by the HIV-1 strain infecting the patient, a finding that was confirmed by sequencing RNA in the HIV *env* region. The ultradeep sequencing analysis revealed a proportion of 2.9% for the X4 and dual-tropic variants combined.

RECIPIENT CHIMERISM

With ongoing engraftment, the PCR patterns of *CCR5* were transformed, indicating a shift from a heterozygous genotype to a homozygous delta32/delta32 genotype (Fig. 1). Complete chimerism, determined on the basis of allelic short tandem repeats, was obtained 61 days after allogeneic stem-cell transplantation.

CELLULAR AND HUMORAL IMMUNE RESPONSES

T-cell responses to defined HLA-A2–restricted antigens, determined with the use of an interferon-γ enzyme-linked immunospot assay, revealed elevated frequencies of HIV-specific T cells before stem-cell transplantation and undetectable frequencies after transplantation (Fig. 2A). Immunoblot analysis revealed a predominant loss of antibodies to polymerase and capsid proteins after

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

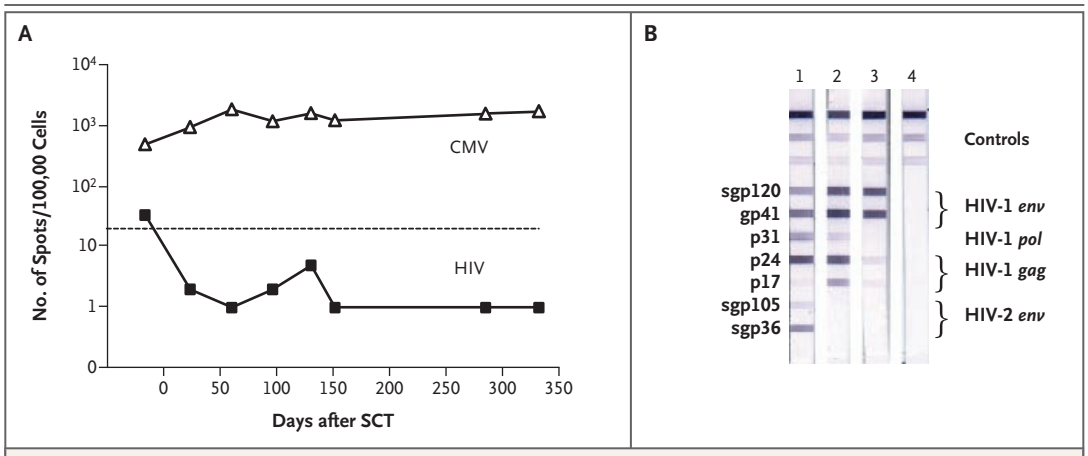

Figure 2. Cellular and Humoral Immune Response to HIV-1.

The results of interferon-γ enzyme-linked immunospot assays are plotted as the mean number of spots per 100,000 peripheral-blood monocytes (Panel A). A positive response was defined as more than 20 spots per 100,000 monocytes. T-cell reactivity was tested against HIV-$1_{476-484}$ (ILKEPVHGV) and cytomegalovirus (CMV)$_{65-73}$ (NLVPMVATV). Whereas specific T-cell responses against CMV increased after transplantation, the patient lost T-cell reactivity against HIV. The results of immunoblot analysis of HIV antigens (Panel B) are shown for a positive control (lane 1), a sample obtained from the patient 14 days before stem-cell transplantation (SCT) (lane 2), a sample obtained from the patient 625 days after transplantation (lane 3), and a negative control (lane 4). Whereas antibodies against envelope proteins still remained detectable in lane 3, the number of antibodies against polymerase and capsid proteins declined markedly. The abbreviation sgp denotes soluble glycoprotein, gp glycoprotein, and p protein.

transplantation, whereas levels of antibodies to soluble glycoprotein 120 and glycoprotein 41 remained detectable (Fig. 2B).

QUANTIFICATION OF VIREMIA

The HIV-1 load was measured with the use of RNA and DNA PCR assays (Fig. 3). Throughout the follow-up period, serum levels of HIV-1 RNA remained undetectable. Also during follow-up, the semiquantitative assay showed no detectable proviral DNA except on the 20th day after transplantation, for both the *env* and long-terminal-repeat loci, and on the 61st day after transplantation, for the *env* locus.

RECTAL-BIOPSY SPECIMENS

In rectal-biopsy specimens obtained 159 days after transplantation, macrophages showed expression of *CCR5*, whereas a distinct *CCR5*-expressing population was not present in the mucosal CD4+ T lymphocytes (Fig. 4).

DISCUSSION

To enter target cells, HIV-1 requires both CD4 and a coreceptor, predominantly CCR5. Blocking of the preferentially used CCR5 receptor by inhibitors or through gene knockdown conferred antiviral protection to R5-tropic variants.[13,14] The homozygous CCR5 delta32 deletion, observed in approximately 1% of the white population, offers a natural resistance to HIV acquisition. We report a successful transplantation of allogeneic stem cells homozygous for the CCR5 delta32 allele to a patient with HIV.

Although discontinuation of antiretroviral therapy typically leads to a rapid rebound of HIV load within weeks, in this patient, no active, replicating HIV could be detected 20 months after HAART had been discontinued.[15] This observation is remarkable because homozygosity for CCR5 delta32 is associated with high but not complete resistance to HIV-1. This outcome can be explained by the behavior of non-CCR5-tropic variants, such as CXCR4-tropic viruses (X4), which are able to use CXCR4 as a coreceptor. The switch occurs in the natural course of infection, and the proportion of X4 increases with ongoing HAART.[16] Genotypic and phenotypic assays can be used to determine the nature and extent of coreceptor use, but the presence of heterogeneous viral populations in samples from patients limits the sensitivity of the assay.[17] When genotypic analysis was performed in two laboratories applying WebPSSM and geno2pheno prediction algorithms, X4 vari-

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

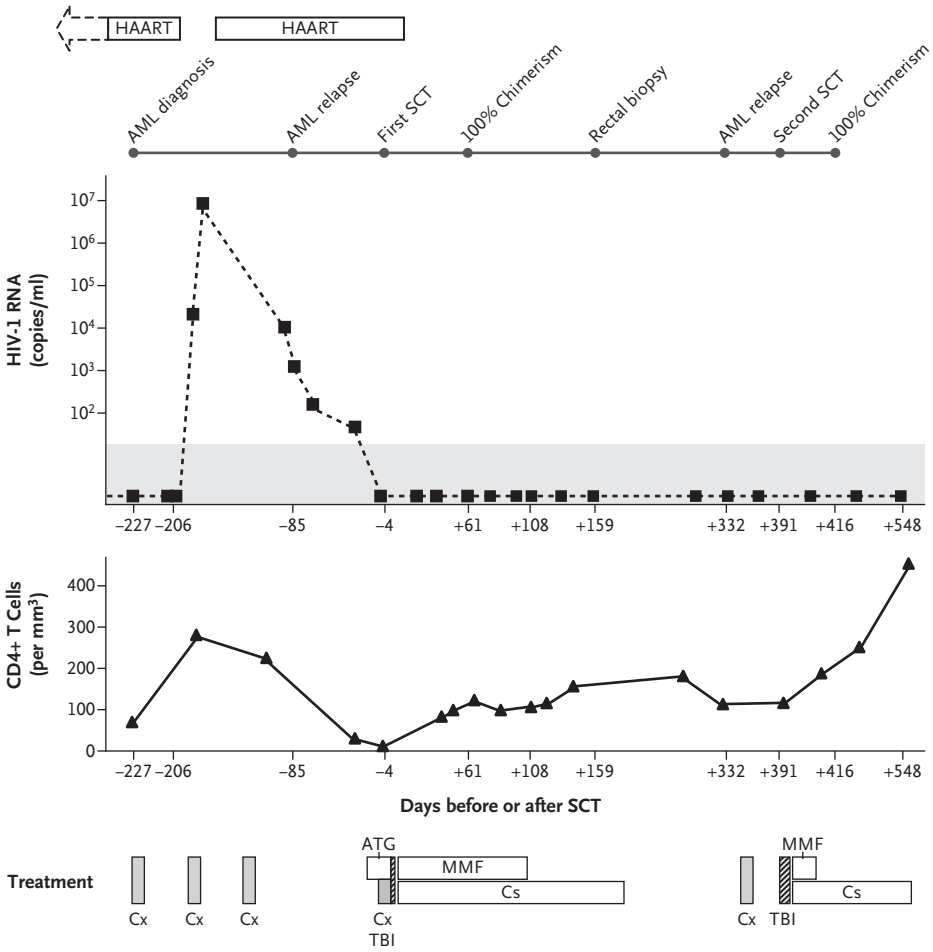

Figure 3. Clinical Course and HIV-1 Viremia.

The clinical course and treatment of acute myeloid leukemia (AML) as well as HIV and the measurement of HIV-1 viremia by means of RNA polymerase-chain-reaction assays are shown from the point of AML diagnosis to day 548 after stem-cell transplantation (SCT). HIV-1 RNA was not detected in peripheral blood or bone marrow from the point at which highly active antiretroviral therapy (HAART) was discontinued, 1 day before SCT, until the end of follow-up, 548 days after SCT. (The shaded area of this graph indicates the limit of detection of the HIV–RNA assay.) The CD4+ T-cell count in the peripheral blood is shown in reference to the immunosuppressive treatments. ATG denotes antithymocyte globulin, Cs cyclosporine, Cx chemotherapy, MMF mycophenolate mofetil, and TBI total-body irradiation.

ants were not detected in the plasma of our patient. To determine the proportion of minor variants in the plasma, we performed an ultradeep sequencing analysis, which revealed a small proportion of X4 variants before the allogeneic stem-cell transplantation.

Even after prolonged HAART, the persistence of HIV-1 populations in various anatomical compartments can be observed in patients without detectable viremia.[18] In particular, the intestinal lamina propria represents an important reservoir of HIV-1, and genomic virus detection is possible in patients without viremia.[19] In this patient, a rectal biopsy performed 159 days after transplantation revealed that CCR5-expressing macrophages were still present in the intestinal mucosa, indicating that they had not yet been replaced by the new immune system. Although these long-lasting cells from the host can represent viral reservoirs even after transplantation, HIV-1 DNA could not be detected in this patient's rectal mucosa.

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

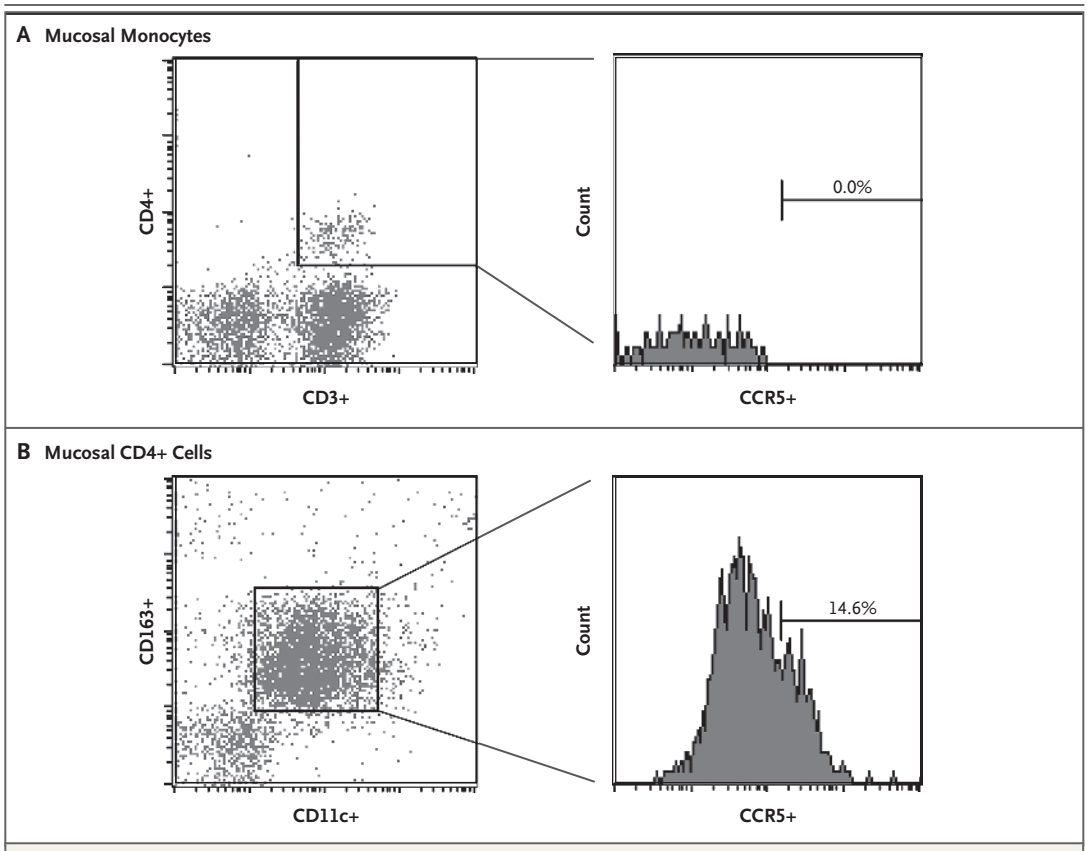

Figure 4. Expression of CD Surface Antigen and Chemokine Coreceptor in the Patient's Rectal Mucosa.
Mucosal cells isolated from rectal-biopsy specimens obtained 159 days after stem-cell transplantation were activated by phytohemagglutinin and analyzed with the use of flow cytometry. Cells were gated for lymphocytes by their characteristic forward- and side-scatter profile and were analyzed for *CCR5* expression within the CD4+ T-cell population (Panel A). Macrophages were identified as CD11c+ and CD163+ within the CD4+ cell gate and analyzed for *CCR5* expression (Panel B). Whereas intestinal CD4+ T lymphocytes were negative (0.0%) for *CCR5* expression, 14.6% of macrophages expressed *CCR5* after engraftment, indicating a complete exchange of intestinal CD3+/CD4+ lymphocytes but not of intestinal CD3+/CD4+ macrophages.

It is likely that X4 variants remained in other anatomical reservoirs as potential sources for reemerging viruses, but the number of X4-tropic infectious particles after transplantation could have been too low to allow reseeding of the patient's replaced immune system.

The loss of anti-HIV, virus-specific, interferon-γ–producing T-cells during follow-up suggests that HIV antigen stimulation was not present after transplantation. This disappearance of effector T cells was not associated with a deficient immune reconstitution, as shown by the absence of relevant infection or reactivation of other persistent viruses, such as CMV and Epstein–Barr virus. Thus, the absence of measurable HIV viremia in our patient probably represents the removal of the HIV immunologic stimulus.[20] Antibodies against HIV-envelope antigens have remained detectable, but at continually decreasing levels. The sustained secretion of antibodies might be caused by long-lived plasma cells that are relatively resistant to common immunosuppressive therapies.[21,22]

In the past, there were several attempts to control HIV-1 infection by means of allogeneic stem-cell transplantation without regard to the donor's *CCR5* delta32 status, but these efforts were not successful.[23] In our patient, transplantation led to complete chimerism, and the patient's peripheral-blood monocytes changed from a heterozygous to a homozygous genotype regarding the *CCR5* delta32 allele. Although the patient had non–*CCR5*-tropic X4 variants and HAART was discontinued

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.

for more than 20 months, HIV-1 virus could not be detected in peripheral blood, bone marrow, or rectal mucosa, as assessed with RNA and proviral DNA PCR assays. For as long as the viral load continues to be undetectable, this patient will not require antiretroviral therapy. Our findings underscore the central role of the CCR5 receptor during HIV-1 infection and disease progression and should encourage further investigation of the development of CCR5-targeted treatment options.

Supported by a grant from the German Research Foundation (DFG KFO grant 104 1/1).

Dr. Hofmann reports serving as a consultant or advisory-board member and on speakers' bureaus for Celgene and Novartis. No other potential conflict of interest relevant to this article was reported.

We thank Alexander Schmidt, Petra Leuker, and Gerhard Ehninger (German Bone Marrow Center, Tübingen and Dresden, Germany) for their encouragement and cooperation regarding access of donor blood samples; Emil Morsch (Stefan Morsch Foundation, Birkenfeld, Germany) and Martin Meixner (Department of Biochemistry, Charité Universitätsmedizin, Berlin) for performing sequencing; Stephan Fuhrmann and Mathias Streitz (Department of Immunology, Charité Universitätsmedizin, Berlin) for providing HIV p24 antigens; Alexander Thielen (Max-Planck-Institut für Informatik, Saarbrücken, Germany) for performing 454 ultradeep-sequencing data analysis; Lutz Uharek (Department of Hematology, Charité Universitätsmedizin) for clinical supervision of the allogeneic stem-cell transplantation; and Martin Raftery (Institute of Medical Virology, Charité Universitätsmedizin, Berlin) for reading an earlier version of this article.

REFERENCES

1. Liu R, Paxton WA, Choe S, et al. Homozygous defect in HIV-1 coreceptor accounts for resistance of some multiply-exposed individuals to HIV-1 infection. Cell 1996;86:367-77.

2. Ayash LJ, Ratanatharathorn V, Braun T, Silver SM, Reynolds CM, Uberti JP. Unrelated donor bone marrow transplantation using a chemotherapy-only preparative regimen for adults with high-risk acute myelogenous leukemia. Am J Hematol 2007;82:6-14.

3. Palella FJ Jr, Delaney KM, Moorman AC, et al. Declining morbidity and mortality among patients with advanced human immunodeficiency virus infection. N Engl J Med 1998;338:853-60.

4. Sora F, Antinori A, Piccirillo N, et al. Highly active antiretroviral therapy and allogeneic CD34(+) peripheral blood progenitor cells transplantation in an HIV/HCV coinfected patient with acute myeloid leukemia. Exp Hematol 2002;30:279-84.

5. Schmid C, Weisser M, Ledderose G, Stötzer O, Schleuning M, Kolb HJ. Dose-reduced conditioning before allogeneic stem cell transplantation: principles, clinical protocols and preliminary results. Dtsch Med Wochenschr 2002;127:2186-92. (In German.)

6. Delobel P, Nugeyre MT, Cazabat M, et al. Population-based sequencing of the V3 region of env for predicting the coreceptor usage of human immunodeficiency virus type 1 quasispecies. J Clin Microbiol 2007;45:1572-80.

7. Däumer M, Kaiser R, Klein R, Lengauer T, Thiele B, Thielen A. Inferring viral tropism from genotype with massively parallel sequencing: qualitative and quantitative analysis. Presented at the XVII International HIV Drug Resistance Workshop, Sitges, Spain, June 10–14, 2008. (Accessed January 26, 2009, at http://domino.mpi-inf.mpg.de/intranet/ag3/ag3publ.nsf/MPGPublications?OpenAgent&LastYear.)

8. Moos V, Kunkel D, Marth T, et al. Reduced peripheral and mucosal Tropheryma whipplei-specific Th1 response in patients with Whipple's disease. J Immunol 2006;177:2015-22.

9. Blau IW, Schmidt-Hieber M, Leschinger N, et al. Engraftment kinetics and hematopoietic chimerism after reduced-intensity conditioning with fludarabine and treosulfan before allogeneic stem cell transplantation. Ann Hematol 2007;86:583-9.

10. Ganepola S, Gentilini C, Hilbers U, et al. Patients at high risk for CMV infection and disease show delayed CD8+ T-cell immune recovery after allogeneic stem cell transplantation. Bone Marrow Transplant 2007;39:293-9.

11. Cassol S, Salas T, Arella M, Neumann P, Schechter MT, O'Shaughnessy M. Use of dried blood spot specimens in the detection of human immunodeficiency virus type 1 by the polymerase chain reaction. J Clin Microbiol 1991;29:667-71.

12. Drosten C, Seifried E, Roth WK. TaqMan 5′-nuclease human immunodeficiency virus type 1 PCR assay with phage-packaged competitive internal control for high-throughput blood donor screening. J Clin Microbiol 2001;39:4302-8.

13. Mueller MC, Bogner JR. Treatment with CCR5 antagonists: which patient may have a benefit? Eur J Med Res 2007;12:441-52.

14. Anderson J, Akkina R. Complete knockdown of CCR5 by lentiviral vector-expressed siRNAs and protection of transgenic macrophages against HIV-1 infection. Gene Ther 2007;14:1287-97.

15. Jubault V, Burgard M, Le Corfec E, Costagliola D, Rouzioux C, Viard JP. High rebound of plasma and cellular HIV load after discontinuation of triple combination therapy. AIDS 1998;12:2358-9.

16. Delobel P, Sandres-Saune K, Cazabat M, et al. R5 to X4 switch of the predominant HIV-1 population in cellular reservoirs during effective highly active antiretroviral therapy. J Acquir Immune Defic Syndr 2005;38:382-92.

17. Skrabal K, Low AJ, Dong W, et al. Determining human immunodeficiency virus coreceptor use in a clinical setting: degree of correlation between two phenotypic assays and a bioinformatic model. J Clin Microbiol 2007;45:279-84.

18. Delobel P, Sandres-Saune K, Cazabat M, et al. Persistence of distinct HIV-1 populations in blood monocytes and naive and memory CD4 T cells during prolonged suppressive HAART. AIDS 2005;19:1739-50.

19. Fackler OT, Schäfer M, Schmidt W, et al. HIV-1 p24 but not proviral load is increased in the intestinal mucosa compared with the peripheral blood in HIV-infected patients. AIDS 1998;12:139-46.

20. Kiepiela P, Ngumbela K, Thobakgale C, et al. CD8+ T-cell responses to different HIV proteins have discordant associations with viral load. Nat Med 2007;13:46-53.

21. Wahren B, Gahrton G, Linde A, et al. Transfer and persistence of viral antibody-producing cells in bone marrow transplantation. J Infect Dis 1984;150:358-65.

22. Manz RA, Moser K, Burmester GR, Radbruch A, Hiepe F. Immunological memory stabilizing autoreactivity. Curr Top Microbiol Immunol 2006;305:241-57.

23. Huzicka I. Could bone marrow transplantation cure AIDS? Med Hypotheses 1999;52:247-57.

Copyright © 2009 Massachusetts Medical Society.

The New England Journal of Medicine
Downloaded from www.nejm.org by JULES LEVIN on December 11, 2010. For personal use only. No other uses without permission.
Copyright © 2009 Massachusetts Medical Society. All rights reserved.