RAPID COMMUNICATION

Inhibition of Productive Human Immunodeficiency Virus-1 Infection by Cobalamins

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Various cobalamins act as important enzyme cofactors and modulate cellular function. We investigated cobalamins for their abilities to modify productive human immunodeficiency virus-1 (HIV-1) infection of hematopoietic cells in vitro. We show that hydroxocobalamin (OH-Cbl), methylcobalamin (Me-Cbl), and adenosylcobalamin (Ado-Cbl) inhibit HIV-1 infection of normal human blood monocytes and lymphocytes. The inhibitory effects were noted when analyzing the monocytotropic strains HIV-1-BaL and HIV-1-ADA as well as the lymphocytotropic strain HIV-1-LAI.

PRODUCTIVE CELLULAR infection with human immunodeficiency virus-1 (HIV-1) is controlled by several different viral and host cell factors. Recent work by other investigators has shown that heme and certain porphyrins can inhibit HIV-1 infection of cells in vitro² and that the effects are apparently mediated by inhibition of viral envelope-cellular CD4 binding.³,⁴ Because of the structural similarities of heme and cobalamins, we sought to determine if cobalamins could modify HIV-1 infection of cells in vitro. We note in the series of experiments reported here that various cobalamin derivatives inhibit the ability of HIV-1 to cause productive infection of human monocytes (Mo) and normal blood lymphocytes (peripheral blood mononuclear cells [PBMC]).

MATERIALS AND METHODS

Cells. Monocytes and PBMC were isolated and cultured as noted before.⁵ In brief, monocytes were isolated by sequential ficoll-sodium diatrizoate and Percoll gradients with subsequent adherence to cultureware plastic and then cultured in Dulbecco's modified Eagle medium (GIBCO, Grand Island, NY) with 10% unheated human serum. Mitogen-simulated PBMC were prepared as noted before using anti-CD3 and anti-CD28 antibodies with interleukin-2 (IL-2).⁶ Jurkat, CEM, HL-60, and U937 cells were from American Type Culture Collection (Baltimore, MD). They were cultured in RPMI-1640 with 10% fetal bovine serum (HyClone, Logan, UT). OM-10.1 cells were a gift from Dr Clay Smith (Duke University, Durham, NC). All experiments were performed in conventional tissue culture laboratories under reduced light but not in absolute darkness.

Viruses, viral reverse transcriptase (RT) assay, gp120-CD4 binding assay, p24 assay, polymerase chain reaction (PCR) assays, and interferon-α (IFN-α) assays. The monocytotropic strain HIV-1-BaL and the lymphocytotropic strain HIV-1-ADA are maintained in our laboratory as noted before.⁷ RT was measured as described before using a phosphoimager device for quantification. Binding of recombinant gp120 to recombinant soluble CD4 was performed in microtiter plates using reagents from Genetech (South San Francisco, CA). In brief, wells were first coated with 200 ng of gp120 and CD4 (40 ng in 0.1 mL of phosphate-buffered saline [PBS]) was added with varying amounts of the designated cobalamins to allow binding. Bound CD4 was then detected using a horseradish peroxidase-conjugated anti-CD4 monoclonal antibody. HIV-1 p24 antigen was measured using a capture enzyme-linked immunosorbent assay (ELISA) method (Coulter, Inc, Hialeah, FL). The PCR-based assay for newly synthesized viral DNA was performed as noted before.⁷ In brief, cells were inoculated with DNAse-treated virus alone or in the presence of the appropriate cobalamin. Cells were then washed and cultured in medium for 20 hours with 10 μg/mL anti-CD4 antibody (Leu3A from Becton Dickinson, Mountain View, CA) to prevent any further viral entry. This time period simulates a single round of virus infection. Cellular lysates were prepared, and total cellular DNA was subjected to 38 cycles of PCR amplification using primers that flank the nef gene⁸ to generate an approximately 1.2-kb HIV-1-specific PCR product. β-Globin-specific primers were used to assure approximate equal numbers of cells in the samples. IFN-α assays were performed using the specific enzyme-linked immunosorbent assay (ELISA) BioSource International (Camarillo, CA), an assay that can detect IFN-α down to a minimum of 10 pg/mL.

Cobalamins. Cobalamins were from Sigma Chemical Co (St Louis, MO) or ICN (Costa Mesa, CA); cobalamins from either source gave comparable results. The cobalamins had extremely low endotoxin content, as determined by Limulus amebocyte lysate testing (Whittaker Bioproducts, Walkersville, MD). When tested as a 3 mmol/L solution, the cobalamins had less than 0.25 EU/mL.

RESULTS

OH-Cbl, Me-Cbl, Ado-Cbl, and cyanocobalamin (CN-Cbl) were not toxic for Mo, PBMC, or cells of the human leukemia cell lines Jurkat, CEM, HL-60, or U937 at concentrations ≤1,000 μmol/L (Fig 1). When added to the cultures of monocytes or PBMC at the time of viral inoculation and left in throughout the culture period, there was potent inhibition of productive infection as judged by supernatant medium RT

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Fig 1. Effect of CN-Cbl, OH-Cbl, Me-Cbl, and Ado-Cbl on HIV-1 infection of monocytes, lymphocytes, and hematopoietic cell line cells. (A) Effects of OH-Cbl on HIV-1-BaL infection of monocytes. Monocytes were inoculated on the day of isolation with HIV-1-BaL (MOI ~ 0.001) and cultured with OH-Cbl for 14 days. Supernatant medium RT was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicate samples). (B) Effects of CN-Cbl, OH-Cbl, and Ado-Cbl on HIV-1-BaL infection of monocytes. Monocytes were inoculated on the day of isolation with HIV-1-BaL (MOI ~ 0.001) and cultured with the designated cobalamin for 14 days. Supernatant medium RT was then measured. In results not shown, Me-Cbl had inhibitory actions comparable to that of OH-Cbl and Ado-Cbl. Comparable patterns of inhibition were seen with HIV-1-ADA (data not shown). Results are displayed as fraction of control RT activity (mean ± SEM of triplicate samples). (C) Effects of CN-Cbl, OH-Cbl, Me-Cbl, and Ado-Cbl on HIV-1-LAI infection of PBL. PBL were inoculated with HIV-1-LAI (MOI ~ 0.001) and cultured with the designated cobalamins for 14 days. Fresh media was added every 2 days. RT activity in supernatant medium sampled on day 14 was measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicate samples). (D) Effects of OH-Cbl on HIV-1-LAI infection of leukemia cell line cells. Cells of the T-lymphoblast cell lines Jurkat and CEM, the myeloblast cell line HL-60, and the monoblast cell line U937 were inoculated with HIV-1-LAI (MOI ~ 0.001) and cultured with OH-Cbl for 8 days. Supernatant medium RT was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicate samples). Cobalamins were not toxic for Mo, lymphocytes, and leukemia cell line cells as determined by morphology under phase microscopy, Wright staining of methanol-fixed cells, trypan blue exclusion, and thymidine incorporation (PBL and cell line cells) (data not shown).

activity and the formation of monocyte syncytia (multinucleated giant cells; Figs 1A, B, C and 2). The concentration required for 50% inhibition (IC50) was approximately 2 to 4 μmol/L when assessed in monocytes and 25 to 50 μmol/L in normal PBL. CN-Cbl exhibited little or no inhibitory activity in all experiments using monocytes and PBL. If we assayed supernatant medium p24 antigen instead of RT as a measurement of viral infection in monocytes, OH-Cbl caused a comparable inhibition (data not shown). Me-Cbl and Ado-Cbl (but not CN-Cbl and OH-Cbl) are light-sensitive and are rapidly converted primarily to OH-Cbl. Thus, it is likely that in our experiments (which were performed under reduced light, but...
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Fig 2. Effects of OH-Cbl on multinucleated giant cell (syncytium) formation in monocytes inoculated with HIV-1-BaL. Monocytes were inoculated with HIV-1-BaL (MOI ~ 0.001) and cultured with or without 34 μmol/L OH-Cbl or 500 μmol/L CN-Cbl for 14 days. The cells were then rinsed with saline, fixed with 100% methanol, and stained with Wright-Giemsa stain. Populations of monocytes not inoculated with virus (A, C, and E) are generally mononuclear, whereas those inoculated with HIV-1-BaL cultured alone (B) or with CN-Cbl (F) have numerous multinucleated giant cells. Populations of HIV-1-inoculated monocytes cultured with OH-Cbl (D) do not have multinucleated giant cells. Comparable effects were noted in doses ranging from 34 to 1,000 μmol/L using each cobalamin. (Wright stain; original magnification x 200.)

not absolute darkness) significant fractions of Me-Cbl and Ado-Cbl were converted to OH-Cbl in vitro.

Although OH-Cbl, Me-Cbl, and Ado-Cbl inhibited HIV-1 infection of these primary, normal leukocytes, they had much less inhibitory effect on the infection of cells of the human T lymphoblast lines Jurkat and CEM, the myeloblastic line HL-60, or the monoblastic line U937 (Fig 4D). The inhibition of productive infection was not strain specific—OH-Cbl, Me-Cbl, and Ado-Cbl inhibited infection of monocytes with the monocytotropic strains HIV-1-BaL or HIV-1-ADA or of PBL with HIV-1-BaL or the lymphocytotropic strain HIV-1-LAI. The cobalamins did not inhibit RT activity. If we added 1 to 1,000 μmol/L CN-Cbl, OH-Cbl, Me-Cbl, or Ado-Cbl to cell-free medium containing RT, none of the cobalamins modified RT activity (data not shown).

If monocytes were pretreated with 250 μmol/L OH-Cbl for 24 hours, washed well, and then inoculated with HIV-1-BaL, the OH-Cbl-treated cells were protected against HIV-1 infection (Fig 3A). However, the degree of inhibition was less than that in cultures in which OH-Cbl was present throughout the culture period. If monocytes were incubated simultaneously with 250 μmol/L OH-Cbl and HIV-1 for 4 hours, washed, and then cultured for 10 days, OH-Cbl-treated cells expressed less viral RT (Fig 3B). When monocytes were inoculated with HIV-1 and cultured for 6 days (a time at which they displayed multinucleated giant cell formation and RT production), washed thoroughly, and then cultured for 10 more days with 250 μmol/L OH-Cbl, there was no inhibition of their subsequent production of RT (Fig 3C). To determine if OH-Cbl would inhibit the ability of latently infected leukemia cells to produce RT after stimulation with tumor necrosis factor (TNF), we treated OM-10.1 cells (an HL-60 cell line with stably integrated proviral HIV-1) with 500 U/mL TNF (with varying amounts of OH-Cbl). OH-Cbl caused only slight decreases in the expression of the induced viral RT (Fig 3D). The inability of the cobalamins to effectively inhibit HIV-1 production in previously infected monocytes and in latently infected leukemia cells is similar to that seen when using drugs such as the RT inhibitors zidovudine, didanosine, and zalcitabine.

HIV-1 binds to cells principally via interaction with cell membrane CD4. Other investigators have shown that heme and various porphyrins inhibit HIV-1 infection and that this inhibition generally parallels the compounds’ abilities to block gpl20-CD4 binding. To determine if cobalamins modified the binding of HIV-1 gp120 to CD4, we tested the ability of CN-Cbl, OH-Cbl, Me-Cbl, or Ado-Cbl to block binding of recombinant CD4 with gp120 from HIV-1-LAI or HIV-1-MN (Fig 4A and B). None of the cobalamins inhibited binding. Likewise, neither CN-Cbl nor OH-Cbl inhibited early steps in the life cycle of HIV-1-BaL in monocytes (viral-cell fusion, viral entry, and reverse transcription; Fig 4C).

It was possible that the cobalamins induced an intrinsic HIV-1 resistance system (eg, induction of IFN-α) within the cells. To determine if cobalamins might induce cellular production of IFN-α (which could then render cells resistant to HIV-1 infection), we treated monocytes with 15 to 500 μmol/L CN-Cbl or OH-Cbl for 3 days and measured IFN-α in the supernatant media using a sensitive ELISA. IFN-α production was not induced by the cobalamin treatments; eg, the supernatant fluid of monocytes cultured 3 days in media with 10% human serum contained 71 ± 1 pg/mL IFN-α, whereas that of monocytes cultured in media with 10% human serum and 500 μmol/L OH-Cbl contained 74 ± 5 pg/mL and that of monocytes cultured in media with 10% human serum and 500 μmol/L CN-Cbl contained 71 ± 1 pg/mL. Likewise, monocytes inoculated with HIV-
Fig 3. Effects of OH-Cbl on HIV-1 productive infection by pretreatment of cells with OH-Cbl before inoculation, by coincubation of OH-Cbl with virus during inoculation, by treatment of previously infected monocytes, or by treatment of latently infected myeloid cells. (A) Inhibition of HIV-1 infection of monocytes by OH-Cbl pretreatment. Monocytes were treated for 24 hours with varying amounts of OH-Cbl. The cells were then washed twice with PBS and then inoculated with HIV-1-BaL (MOI ~0.001) and cultured for 14 days. Supernatant medium RT activity was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicates). (B) Inhibition of HIV-1 infection of monocytes by coincubation with OH-Cbl during the viral inoculation step. Cells were incubated with HIV-1-BaL (MOI ~0.001) with varying amounts of OH-Cbl for 4 hours and then washed twice with PBS to remove unbound cobalamin and virus. They were then cultured for 14 days without further addition of virus or OH-Cbl. Supernatant medium RT activity was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicates). (C) Lack of inhibitory effect of OH-Cbl on viral production by previously infected monocytes. Monocytes were inoculated with HIV-1-BaL (MOI ~0.001) and cultured for 7 days. The cells were then twice with PBS and incubated for 3 more days with different amounts of OH-Cbl. Supernatant medium RT activity was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicates). (D) Effect of OH-Cbl on induction of viral production by TNF-treated, latently infected OM-10.1 cells. The cells were treated with 500 U/mL recombinant human TNF with varying amounts of OH-Cbl for 3 days. Supernatant medium RT activity was then measured. Results are displayed as fraction of control RT activity (mean ± SEM of triplicates). Control OM-10.1 cells not treated with TNF did not express any RT activity.

DISCUSSION

Cobalamins are polycyclic compounds containing a cobalt within the corrin ring, an upper axial ligand for the cobalt (eg, cyano-, hydroxo-, methyl-, or adenosyl-), and a dimethylbenzimidazole nucleotide moiety that forms the lower axial cobalt ligand. Cobalamins are absorbed from the gut into the blood by processes that require the proteins intrinsic factor and transcobalamin II (TC-II). They are transported in the blood bound to TC-II; the Cbl–TC-II complex enters cells after binding to TC-II membrane receptors. CN-Cbl (vitamin B12) is a relatively nonreactive, stabilized cobalamin that is not found normally in the body. It is used pharmacologically for the treatment of B12 deficiency states in humans. In vivo, cyanide is removed from the cobalt with production of OH-Cbl, which is responsible for the antiviral effects observed in this study.
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Fig 4. Lack of effect of cobalamin on early events of HIV-1 life cycle. (A and B) Effect of CN-Cbl, OH-Cbl, Me-Cbl, and Ado-Cbl on CD4-gp120 binding. Results from experiments using gp120 from HIV-1-LA1 (A) or from HIV-1-MN (B) are displayed as optical density (od; means ± SEM of quadruplicate samples). Serum from an HIV-1-infected person containing anti-gp120 antibody served as the noted positive control, whereas serum from an individual without infection and antibodies served as a negative control. (C) Effect of OH-Cbl or CN-Cbl on HIV-1-BaL infection of monocytes. To determine whether the cobalamin derivatives targeted an early step in the virus life cycle, we adapted a modified PCR-based assay for newly synthesized viral DNA. Monocytes were cultured for 7 days, washed twice with PBS, and then incubated for 2 hours with HIV-1-BaL (DNAse-treated HIV-1-BaL, MOI = 0.01) alone or in the presence of 333 μmol/L CN-Cbl or OH-Cbl. Cells were then washed and cultured in medium for 20 hours with 10 μg/ml anti-CD4 antibody (Leu3A from Becton Dickinson) to prevent any further viral entry. This time period simulates a single round of virus infection. Cellular lysates were prepared, and total cellular DNA was subjected to 38 cycles of PCR amplification using primers that flank the nef gene to generate an approximately 1.2-kb HIV-1-specific PCR product. Results show that neither CN-Cbl nor OH-Cbl prevent entry of HIV-1-BaL into monocytes and subsequent viral DNA formation. Similar analyses using β-globin-specific primers showed approximately equivalents amounts of cellular DNA per sample (data not shown). Lane 1, no cells (water; negative control); lane 2, cells with HIV-1; lane 3, cells with HIV-1 and 333 μmol/L OH-Cbl; lane 4, cells with HIV-1 and 333 μmol/L CN-Cbl; lane 5, cells with 333 μmol/L OH-Cbl but no virus; lanes 6 through 11, HIV-1 plasmid DNA in decreasing copy numbers (approximately 3,000, 1,500, 800, 400, 200, and 100, respectively); and lane 12, 1-kb DNA ladder markers.

of OH-Cbl. OH-Cbl is converted to Me-Cbl or Ado-Cbl, and these are cofactors for enzymes including methionine synthase (Me-Cbl) and methylmalonyl CoA mutase (Ado-Cbl). Cobalamin deficiency results in neurologic and hematologic abnormalities. In comparison to CN-Cbl, OH-Cbl is better retained in the body, more bioavailable to cells, and more efficiently processed by cells in vitro to active cobalamin cofactors. This could explain in part the relative ineffectiveness of CN-Cbl as an inhibitor. The cell-specific inhibition effects (inhibition in normal monocytes and lymphocytes, but less in cell line cells) could be related to differences in TC-II receptors, with cells of some types being able to take up and accumulate more of the cobalamin. Alternately, cells of some types might have unique abilities to convert the cobalamin to a derivative with antiviral activity. The inhibition of HIV-1 infection appears to be pretranscriptional and not related to early steps in the viral life cycle (Figs 3 and 4). Furthermore, the cobalamins do not inhibit reverse transcriptase and, unlike lipopolysaccharide, they do not increase IFN-α production by monocytes.

In addition to participation in important metabolic enzyme reactions, cobalamin may also bind nitric oxide (NO) and modify its actions in vitro and in vivo. In separate work, we have noted that the cobalt of OH-Cbl avidly binds NO.
Pietreforte et al. showed that Crease, 2h,2R,3' Bukrinsky et al. have noted that HIV-1 expression produced within or near an infected cell and by some mechanism inhibit productive HIV-1 infection. It has been noted that NO can activate NF-kB. Because activation of NF-kB can enhance HIV-1 expression, 22 cobalamin quenching of NO could inhibit NF-kB activation and reduce HIV-1 expression.

An appreciable percentage of individuals with HIV-1 infection have been noted to have low levels of vitamin B12, but not all show clinical evidence of vitamin B12 deficiency. Aspects of neurologic disorders and brain pathology seen in those with HIV-1 infection have similarities to those noted in vitamin B12-deficient patients (not infected with HIV-1) with neurologic disease. Dawson et al. have found that brain cells may overproduce NO in response to CNS methyl group metabolism, as judged by cerebrospinal fluid studies, indicating a possible functional CNS deficiency of cobalamins. Also, restoration of cobalamin levels in humans appears to improve information processing in HIV-1-infected subjects. Me-Cbl has been noted to protect against NO-mediated neuronal toxicity in vitro. It is possible that locoregional NO production in the nervous system could serve to modify cobalamins and to create a relative functional deficiency of a compound (cobalamin) capable of inhibiting neurotoxicity mediated by NO produced physiologically during normal nervous tissue function.

Further work will be required to precisely determine the mechanisms by which cobalamins inhibit HIV-1 infection and whether this inhibition extends to other HIV strains and to primary HIV-1 isolates. Other cobalamin analogues may be discovered with more potent anti-HIV-1 activity. It is important to note that cobalamins used therapeutically in humans are generally nontoxic. OH-Cbl has been administered in very high doses to humans for treatment of cyanide poisoning. Noted side effects are minimal and include red-colored urine and transient high blood pressure (presumably because of OH-Cbl binding and quenching of NO). Based on our in vitro findings, we propose that experimental treatment of HIV-1-infected patients with high doses of OH-Cbl might (in a nontoxic fashion) inhibit HIV-1 infection in vivo.

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