Inability to recognize incident infection has traditionally limited both scientific and public health approaches to HIV disease. Recently, some laboratories have begun adding HIV nucleic acid amplification testing to HIV diagnostic testing algorithms so that acute (antibody-negative) HIV infections can be routinely detected within the first 1–3 weeks of exposure. In this review article, we will highlight critical opportunities for HIV treatment and prevention that are presented by these diagnostic strategies.
Acute HIV revisited: new opportunities for treatment and prevention

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Inability to recognize incident infection has traditionally limited both scientific and public health approaches to HIV disease. Recently, some laboratories have begun adding HIV nucleic acid amplification testing to HIV diagnostic testing algorithms so that acute (antibody-negative) HIV infections can be routinely detected within the first 1–3 weeks of exposure. In this review article, we will highlight critical opportunities for HIV treatment and prevention that are presented by these diagnostic strategies.

Acute HIV infection

The natural history of HIV infection encompasses an acute/primary phase that lasts months, followed by an early/clinically latent phase that typically lasts 3–10 years, and ultimately by the immune collapse characterized by AIDS. “Acute” HIV infection best describes the interval during which HIV can be detected in blood serum and plasma before the formation of antibodies routinely used to diagnose infection. During this time, high levels of viremia and shedding at mucosal sites can be demonstrated, because HIV replication is unrestrained by immune responses. Approximately 30 days after infection, early virus-specific immune responses are mounted, with subsequent reduction of viremia. After 4–6 months, viral and host factors combine to determine a new pseudo–steady state of viremia (or virologic “set point”) for each patient, heralding the beginning of the long clinical latency experienced by patients infected by HIV.

Recognition of acute HIV infection is important for several reasons. First, acute HIV provides a unique view of HIV transmission and pathogenesis, including early host-virus interactions that require further study. Second, prevention strategies directed at subjects with acute HIV infection may have great impact. Third, very early recognition may allow for HIV treatment that could alter the natural history of disease, or even eliminate infection.

Acute HIV revisited: new possibilities for early detection

Despite infection of nearly 60 million individuals worldwide with HIV, fewer than 1,000 cases have been diagnosed in the first month of infection, primarily because of a lack of a specific and recognizable acute retroviral syndrome. About half of people with acute HIV infection develop headache, fever, myalgias, anorexia, rash, and/or diarrhea (1–3) after an incubation period of around 14 days (1, 4–6). Symptoms are generally minor and last days to weeks (1). Genital or oral ulcers may be present, and coinfections with other sexually transmitted pathogens (e.g., herpes simplex virus, gonorrhea, syphilis, hepatitis viruses) are common (2, 7–9). The latter observation suggests common cotransmission of HIV and other sexually transmitted disease (STD) pathogens.

Since acute retroviral syndromes mimic many common febrile illnesses, including infectious mononucleosis, influenza, malaria, and rickettsial diseases (1, 10), the true diagnosis (acute HIV) is rarely considered at an initial patient encounter (1, 10–12). The diagnostic challenge in acute HIV infection is made more difficult by the fact that routine HIV antibody tests will typically remain negative for 1–2 weeks beyond the onset of acute retroviral symptoms (26–35 days following initial infection) (5, 13); additional virus-specific diagnostic tests (e.g., HIV p24 antigen ELISA and HIV nucleic acid amplification assays) are needed to detect HIV infection prior to the appearance of antibodies (Figure 1). While HIV nucleic acid amplification assays are now extremely sensitive and can reliably detect HIV by days 9–11 of infection (13, S1), they are vulnerable to false-positive rates as high as 1%. Such tests remain relatively expensive and have not traditionally been used for routine clinical HIV screening.

The blood-banking industry, however, combines antibody and HIV RNA testing to protect the blood supply. Blood banks submit all donations to routine antibody testing; antibody-positive donations are discarded first. They then combine aliquots from a number of antibody-negative donations, to create a specimen pool. The pools are then screened for HIV RNA. An individual donation is therefore only tested for HIV RNA if its pool first screens positive. In this way, only very few individual specimens are tested for HIV RNA — increasing throughput, decreasing costs, and dramatically reducing false-positive results (Figure 2; refs. 14, S2). Pooling strategies for HIV detection in clinical testing have recently been piloted in Swiss (15), Indian (16), and US (14) clinical-HIV-testing populations. The results suggest that HIV RNA testing — if based on pooling of antibody-negative specimens — can efficiently identify acute HIV infections in clinical testing. Especially in clinical-testing populations expected to contain low numbers of acute, antibody-negative infections, pooling affords remarkable increases in cost efficiency and predictive value. Clinical studies have clearly indicated that voluntary counseling and testing (VCT) enhanced to incorporate HIV RNA screening can be both clinically (14) and economically feasible (14, 16).

Furthermore, studies using various detection strategies (including individual tests for HIV RNA or p24 antigen, as well as pooling strategies) have revealed that acute HIV is not as rare in clinical-testing populations as is commonly assumed. Pincus and colleagues (12) found that five (1.0%) of 511 consecutive urgent-care-center attendees with “any viral symptoms” in Boston had acute HIV infection confirmed by seroconversion. Rosenberg and colleagues

Nonstandard abbreviations used: antiretroviral therapy (ART); CC chemokine receptor 5 (CCR5); CXC chemokine receptor 4 (CXCR4); sexually transmitted disease (STD); simian human immunodeficiency virus (SHIV); voluntary counseling and testing (VCT).

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examined specimens submitted for heterophile antibody testing for infectious mononucleosis in a university hospital and found that at least four (0.8%) of 536 sera examined were from acutely HIV-infected patients (11). Three (0.3%) of 1,000 emergency-department attendees with fever in North Carolina (17) and six (0.3%) of 2,300 consecutive, unslected emergency-department attendees in Baltimore (18) had antibody-negative acute HIV. In hyperendemic areas and among patients with STDs, acute HIV infections can be detected even more frequently: 58 (1.2%) of 4,999 patients at an Indian STD clinic had acute HIV (7), and 23 (2.5%) of 928 STD clinic attendees in Lilongwe, Malawi, were found to be acutely HIV-infected (2). While the overall percentage of individuals with acute HIV infection in these studies, in both low- and high-prevalence areas, may appear low, a striking finding was that HIV antibody tests have missed more than 3% of the detectable HIV infections in each testing population. In fact, in Pincus et al.’s and Rosenberg et al.’s studies, antibody-negative infections represented more than 3% of the detectable infections among patients presenting for care with apparent viral symptoms. Together, these results indicate that adding HIV RNA screening to current diagnostic screens can commonly identify acutely infected patients and substantially improve the overall sensitivity of HIV testing for infection.

The North Carolina experience. In collaboration with the state of North Carolina, we have developed the Screening and Tracing of Active Transmission (STAT) program, which incorporates HIV RNA screening into all publicly funded HIV testing performed for HIV Active Transmission (STAT) program, which incorporates HIV RNA VCT by the central State Laboratory of Public Health (approximately one per 50,000 specimens), and the marginal cost of pooling HIV RNA testing has remained low (approximately $2 per specimen) (3). Similar programs are now being launched in other states and abroad. It is therefore critical to revisit the opportunities that detection of acute HIV infection can provide for our understanding of HIV pathogenesis, and for our ability to help patients receive better clinical care and more effective prevention.

The biology of HIV expansion

Initial expansion of viral reservoirs. HIV’s attachment to and entry into cells results from a complex interaction of the HIV envelope proteins gp120 and gp41 with cell surface receptors (CD4 and CC chemokine receptor 5 [CCR5] or CXC chemokine receptor 4 [CXCR4]) that are present on T cells and/or macrophages (19, S3–S7). In acute HIV infection resulting from sexual exposure to HIV-1 (Figure 3), the virus successfully traverses the epithelial layer by one of several proposed mechanisms: transcytosis, epithelial cell capture, or exposure to subepithelial target cells through disruptions in mucosal integrity (reviewed in ref. 20). Mucosal DCs express C-type lectins (e.g., DC-SIGN), which can both specifically bind HIV and facilitate its internalization. HIV-1 that is bound and internalized by a DC may allow infection of nearby CD4CCR5+ cells and/or efficient presentation of HIV-1 to susceptible target cells after DCs migrate to draining lymph nodes (21, S8). However, simian human immunodeficiency virus-infected (SHIV-infected) memory CD4CCR5+ cells have been detected in mucosal tissues of macaques as early as 6 hours after exposure, which suggests the possibility of direct infection (22, S9, S10). Ultimately, HIV-infected CD4+ cells can be found in lymphoid tissue within 2 days of infection, and the magnitude of infection present in these tissues is sufficient to account for the subsequent rise in plasma viremia (23, S11).

Initial viremia expands exponentially, with a doubling time of approximately 0.3 days during the first 2–3 weeks of infection (13, S12–S14). Experimental primate models of mucosal HIV infection have demonstrated that maximal levels of viral expression occur in different tissue compartments sequentially over short periods of time (22, 24, 25). Viral loads in blood, genital secretions (26, 27), and other compartments peak at very high levels around 4 weeks after infection (27) and then decrease in association with the appearance of virus-specific CTL responses (4, 28).

The overall composition of the CD4+ cell population changes during the course of acute HIV infection. Provided the individual does not have another systemic infection, the CD4+ cell population consists predominantly of resting (HLA-DR-CD38-) cells (S15–S19). Increasing HIV-1 replication during acute infection leads to a general activation of CD4+ and CD8+ cells, including HIV-1–specific CD4+ cells. Activated CD4+ cells are likely to be successfully infected with HIV-1 (29); it is therefore likely that the very cells necessary to orchestrate a robust immune response are targeted for destruction during acute infection.

Host-virus interactions: selection, compartmentalization, and diversification. The host-virus interaction shapes the population of HIV variants in systemic and tissue compartments. The number of replication events that occur during acute HIV infection is extremely large, and the opportunity for host factors to exert pressure on existing or newly mutated viral variants is substantial. Host factors exerting early selective pressure may include the cells initially infected, or microenvironments in the mucosa, submucosa, and lymph nodes, which present a variety of innate host defenses including IFNs and/or other molecules (30, 31, S20). Host selective pressures may either decrease or increase the diversity of the infecting-virus population. For example, most acute infections (97%) result from HIV variants that use CCR5, regardless of route of infection (32–35, S21–S25), which suggests some form of selection against variants that use CXCR4.
Establishment of infected cell pools in acute HIV infection. While exponential replication of HIV-1 with attendant CD4 cell activation and loss is the primary dynamic during very early infection, more subtle processes begin at the same time. Small populations of CD4+ cells with a resting memory cell phenotype begin to integrate HIV-1 DNA in the chromosome. Such cells are detected relatively early in HIV infection (36), and at least some cells appear to have a long half-life (S26–S28). Two reservoirs of latently infected cells are likely to exist from early in acute infection, the more abundant one having "pre-integration" HIV-1 and the other having integrated, replication-competent HIV. After initiation of antiretroviral therapy (ART), the two cell subpopulations can be distinguished. Cells with preintegration HIV and a shorter half-life decay, revealing a smaller, long-lived reservoir (37). These long-lived cells are invisible to the immune system and have a decay half-life on the order of 48 months (S26). Such slow decay is explainable either by persistence of infected cells or by continued, low-level viral replication (38, S29). Persistence of quiescent but infected cellular reservoirs makes HIV incurable with current interventions.

The precise dynamics of the establishment of this long-lived reservoir during acute HIV infection are unknown. Two clinical trials have quantified reservoirs of HIV in latently infected CD4+ cells in seronegative acutely HIV-infected patients treated with a standard duration of ART (39, 40). Each found that patients started on therapy while they were still HIV antibody–negative had lower levels of latently HIV-infected CD4+ cells, consistent with the hypothesis that these reservoirs are fully established only toward the end of the acute-infection interval.

The adaptive immune response. Infections with HIV-1 and with related viruses that infect nonhuman primates present a particularly complex interaction with the host immune system, as the primary target cells are critical CD4+ T cells, which are themselves essential to a robust pathogen-specific immune response (reviewed in ref. 41). The initial HIV-1–specific immune response is characterized by the appearance of non-neutralizing antibodies detected by ELISA 2–4 weeks after infection (13, 42). These antibodies serve as the basis for the diagnosis of HIV. However, they have no effect on viral load and appear to exert little selective pressure (43). Neutralizing antibodies are detected 8 weeks or more after infection (43–45), well past the viral-load peak (S30–S33). Neutralizing antibodies seem to place strong immune pressure on the virus, as evidenced by escape variants that appear (44, 45) together with an explosion of viral diversity (43). While neutralizing antibodies exert strong selective pressure, they do not appear to have a sustained effect on HIV (or SHIV) RNA levels in plasma, which demonstrates the ease with which HIV-1 escapes from this immune response (45).

Retrovirus-specific CD8+ CTLs detectable early after infection are strongly associated with control of viremia in acute infection and established infection (4, 41, 46, 47, S34–S36). CTL escape variants can be identified as early as 4 weeks after acute SHIV infection in macaques (S37), and escape variants can establish HIV infection in vertical transmission (48, S38). The initial CTL response(s) may be directed against a few epitopes and subsequently broaden during prolonged antigen stimulation (S39). Epitopes targeted during
acute infection often differ from those recognized during chronic infection (S39, S40). The importance of the CTL response in modulating HIV-1 viremia can be inferred by the association of specific HLA types with low HIV RNA levels and slowed disease progression (49–51; S41, S42); by the demonstration that specific HLA-restricted CTLs are associated with better control of SHIV and HIV replication (S43, S44), even in acute infection (S45); and by selection for viral escape (4, S37). However, all initial CTLs are not created equal. Some specific CTLs in the SHIV model select rapidly for escape variants, while others appear to offer little selective pressure (S46–S48). The avidity of the initial CTL responses may be extremely important, and the ease with which virus can escape highly avid responses may dictate the level of control. However, multiple previously unrecognized CTLs may be present (S39), and the sequence of events leading to effective CTL responses during acute HIV infection is not clear. In particular, the potential effects of ART on developing cellular responses is a matter of controversy: in one study, patients in whom ART was initiated before seroconversion demonstrated narrower and lesser-magnitude CTL responses to HIV than did untreated patients (S49).

However, HIV-specific CD4+ responses may also be an essential component of the initial adaptive immune response (52, 53, S50) and, in acute infection, may be associated with robust CD8+ CTL responses (54, S49). In the study cited above, treatment during acute infection either before or after seroconversion led to higher CD4+ Th cell responses than treatment of chronically infected
patients (S49). There is continued debate over the relative importance of quantitative HIV-1–specific CD4+ cell responses (S51).

**Acute HIV and clinical implications**

A unique role for acute treatment: augmenting host immune control of HIV. Highly potent ART in current use results in significant reversal of disease progression in HIV-infected individuals with advanced disease. Prolonged treatment, however, continues to be limited by drug toxicity, problems with adherence, drug resistance, and cost. To date, the principal rationales for antiretroviral treatment early in acute HIV infection rest on the ability of potent ART (a) to treat some symptomatic patients; (b) to halt viral evolution at a time of minimal viral diversity, prior to viral adaptations to specific host immune responses; (c) to protect developing immune responses from the deleterious effects of sustained HIV viremia; (d) to reduce the viral set point; and (e) to limit the latent pool. Rosenberg and colleagues noted that initiation of ART during the early stages of acute HIV infection led to the development of unusually broad and strong HIV-1–specific Th cell proliferation in response to HIV antigens (S52, S54). These data support the hypothesis that early targeting of HIV-1–specific T cells by HIV may be an important pathogenic mechanism allowing persistent, high-level viral replication in the host after resolution of acute infection (29) — and that early intervention with ART could boost initial host responses to infection. If true, this would suggest that treatment of acute HIV might serve as a method to augment host immunity and might thus obviate or delay the need for lifelong continuous ART. Early observations supported a possible role of ART in the management of acute HIV infection. Anecdotes described patients that experienced prolonged periods of controlled viremia in conjunction with strong, HIV-specific cellular immune responses after discontinuing ART initiated during acute infection (S55, S52). One of the first prospective studies on structured treatment interruption (STI) in acute HIV infection incorporated the concept of viral rebound as antigenic stimulus to enhance T cell responses. The protocol involved treatment interruption after a minimum of 8 months of undetectable viral load, with therapy reinitiated if the viral load increased to greater than 5,000 RNA copies per milliliter plasma for 3 consecutive weeks, or greater than 50,000 copies at one time (S54). Three patients achieved long-term viral suppression after a single treatment cessation. The remainder required re-treatment and a second interruption, after which all individuals experienced transiently suppressed plasma viremia, and two achieved sustained viral suppression. In all cases, interruptions were followed by enhancement in magnitude and breadth of cellular HIV-specific immune responses. This trial lacked a concurrent control population, and a clinically important effect of therapy on HIV RNA levels in patients can only be inferred by comparison with HIV RNA levels previously observed in populations of patients not receiving this therapy, or by observation of delayed rebound of HIV RNA in plasma after a period of relative suppression.

The principal adverse events in early studies have been isolated cases of a retroviral syndrome similar to primary HIV infection, associated with initial discontinuation of therapy (S56, S53). Importantly, prolonged observation of the patients studied in the trial described above has shown that initial immune control of HIV replication can wane 6–30 months after removal from therapy, in association with viral rebound to more typical levels of viremia and concurrent evolution of escape mutations to HIV-specific CTL epitopes or neutralizing antibody (S57, S58). These results emphasize that the benefits of acute treatment may not translate to permanent remission of HIV disease. Still, acute HIV remains the only set-ting in which the natural history of disease may be altered by the temporary use of ART.

The proving ground for curing HIV. The decay of HIV-infected cell populations in patients receiving potent ART resulted in initial enthusiasm for the “eradication hypothesis” (S59). Since then, attempts to cure established HIV infection with antiviral agents have met with absolutely no success. As described above, a subpopulation of HIV-infected CD4+ lymphocytes avoids viral or immune cytolysis and enters the resting state (S27, S54). This reservoir, invisible to the immune system, appears to have a very low
The potential magnitude of the contribution of acute hyperinfectiousness to transmission is revealed by two studies examining the phylogenetic relatedness of viral strains in newly infected patients in defined communities. Among 191 newly infected patients in the Swiss HIV Cohort, 29% shared viral sequences, time of infection, and geography with at least one other acutely infected patient (90). In a similar study in New York, New York, 51 (21%) of 241 patients were found to be clustered, and acute-to-acute transmission was confirmed by history in nine cases (S76). There are two
principal alternative explanations for such extensive clustering. The first is efficient, rapid dissemination by acutely infected individuals, leading to serial infections in sexual networks. However, “core transmission” by a small unidentified subgroup of HIV-positive men or women in the same population could also lead to the same outcome (91, S77). In either scenario, the ability to identify acutely HIV-infected men and women could open a unique window on active HIV transmission taking place in a community, and provide opportunities to interfere with the chain of HIV transmission.

Intervention: targeting prevention to networks with active disease transmission. Traditional surveillance systems, which are based on detection of undifferentiated, prevalent cases of HIV disease, can describe where an epidemic has been, but not where it is going. Because traditional surveillance cannot isolate the context or conditions of HIV incidence, the results cannot describe local forces (socioeconomic, cultural, and geographic) that drive HIV spread in communities (92). Incident STDs can be heavily concentrated in definable social networks and particular locales that are not immediately obvious (93, 94, S78, S79). Identifying local and regional patterns of HIV transmission can allow targeting of high-transmission areas for public health interventions (S60). Reliable information about the locations and correlates of incidence can furthermore ratify information gathered from other sources (e.g., behavioral surveys or cross-sectional serosurveys) and provide early indications of the effectiveness of interventions. The drive to identify regional variation in incidence rates has previously led to development of “detuned” HIV antibody assays that remain negative in some patients with recent infection and low-avidity antibodies; one such assay under evaluation by the Centers for Disease Control and Prevention has proven useful for estimating seroincidence in cross-sectional, population-based samples (95). Unfortunately, the current generation of detuned assays are unable to accurately classify individual patients as having truly recent infection.

One particularly promising approach to HIV control combines identification of acute disease with “network notification,” linking case reporting to the tracing of contacts and offering partner counseling and referral services (96). Applying this strategy prospectively to incident HIV could harness classical infection-control techniques that have been successfully used for decades in tuberculosis- and syphilis-eradication campaigns. Modern epidemiologic techniques can supplement the information provided by STD contact tracing. For instance, spatial analysis based on geographic information systems and correlates of incidence can further validate high-transmission areas for public health interventions (S60). Reliable information about the locations and correlates of incidence can furthermore ratify information gathered from other sources (e.g., behavioral surveys or cross-sectional serosurveys) and provide early indications of the effectiveness of interventions. The drive to identify regional variation in incidence rates has previously led to development of “detuned” HIV antibody assays that remain negative in some patients with recent infection and low-avidity antibodies; one such assay under evaluation by the Centers for Disease Control and Prevention has proven useful for estimating seroincidence in cross-sectional, population-based samples (95). Unfortunately, the current generation of detuned assays are unable to accurately classify individual patients as having truly recent infection.

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