



FROM HIV DIAGNOSIS TO VIRAL SUPPRESSION: RETHINKING CARE-CASCADE FAILURE THROUGH ACTIONABLE SURVEILLANCE, EARLY WARNING, AND TARGETED INTERVENTION

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ABSTRACT

Background: Despite highly effective antiretroviral therapy (ART), substantial losses persist between HIV diagnosis, linkage to care, retention, and durable viral suppression. Conventional care-cascade indicators remain indispensable, but they largely describe attrition after it has occurred, limiting their usefulness for timely intervention. **Objective:** To examine HIV care-cascade failure through a prospective, response-oriented lens and to ask how surveillance systems can identify emerging vulnerability before adverse outcomes become entrenched. **Methods:** Structured narrative review of peer-reviewed literature, national surveillance reports, and public-health guidance on care-cascade disruption, HIV surveillance, cluster detection and response, data integration, predictive analytics, and engagement interventions. **Findings:** Cascade failure is cumulative and multilevel, arising from interacting clinical, structural, and health-system factors rather than individual adherence alone. Surveillance data can be used to relink people to care, and cluster detection and response offers an organisational template in which predefined signals trigger investigation and proportionate action. Predictive models of disengagement show promise, but evidence that they improve outcomes is scarce, and data incompleteness, poor calibration, algorithmic bias, and privacy risk can undermine both effectiveness and equity. **Conclusions:** We propose a Surveillance-to-Suppression Framework comprising seven interconnected functions Detect, Anticipate, Triage, Intervene, Re-engage, Suppress, and Learn that reconceptualises the linear cascade as a learning system in which intervention outcomes continuously inform surveillance and response. Durable viral suppression will require a shift from descriptive cascade monitoring toward anticipatory, actionable, and equitable surveillance that is matched by investment in response capacity.

KEYWORDS: HIV; care cascade; viral suppression; public health surveillance; early warning; retention in care; Data to Care; cluster detection and response; predictive analytics; health equity.

Key Messages

- Care-cascade indicators show where people have already been lost; they are poorly suited to showing where loss is beginning.
- Cascade failure is cumulative and multilevel. Missed visits and viral rebound are often downstream signals of structural and health-system failure, not individual non-adherence alone.
- The organisational logic of HIV cluster detection and response predefined signal, investigation, proportionate action, and follow-up can be extended to emerging disengagement and viral non-suppression.
- Predictive accuracy is not public-health effectiveness. Early-warning systems should be judged by actionable lead time, calibration across populations, and demonstrated improvement in outcomes.
- The proposed Surveillance-to-Suppression Framework (Detect, Anticipate, Triage, Intervene, Re-engage, Suppress, Learn) links measurement to response and couples detection capacity with service capacity.

1. INTRODUCTION

1.1 Progress in HIV treatment, persistent failures in continuity of care

The modern HIV treatment era presents a striking paradox. Antiretroviral therapy (ART) has transformed HIV from a frequently fatal infection into a manageable chronic condition. Early treatment reduces serious morbidity and mortality^[1], and sustained viral suppression effectively prevents sexual transmission.^[2–4] Yet these therapeutic advances have not translated uniformly into successful outcomes across the HIV care continuum. The central challenge is increasingly not whether effective treatment exists, but whether people diagnosed with HIV can enter care promptly, remain continuously engaged, and achieve and sustain viral suppression.^[5,6]

This gap remains evident in contemporary U.S. surveillance data. Among more than 1.1 million people with diagnosed HIV at the end of 2024, 77% received HIV medical care, 56% were retained in care, and 69% were virally suppressed. Among people newly diagnosed in 2024, 83.1% were linked to medical care within 1 month, and 71.1% achieved viral suppression within 6 months.^[7] These figures indicate substantial progress, but they also reveal attrition between diagnosis and durable treatment success, with important variation across populations and transmission categories. The consequences extend beyond individual health: modelling studies estimate that most new U.S. HIV transmissions originate from people who are undiagnosed or who have been diagnosed but are not in care or not virally suppressed.^[8,9] Persistent cascade gaps therefore threaten both national^[10] and global^[11] targets for ending the HIV epidemic.

The HIV care continuum remains indispensable for making these losses visible because it conceptualises care as a sequence extending from diagnosis through linkage, receipt and retention in care, and sustained viral suppression.^[5,12] As Ayo-Ige et al.^[13] argue, breakdowns across this continuum can undermine the population-level effectiveness of otherwise highly efficacious HIV treatment.

1.2 The limitation of viewing the cascade retrospectively

The analytical strength of the care cascade is also one of its limitations. Conventional cascade indicators describe well where attrition has already occurred, but they are less suited to determining where failure is beginning and whether intervention can occur before disengagement becomes prolonged. A low retention or viral-suppression rate identifies an important programmatic deficit. It does not, by itself, reveal which individuals, networks, communities, or geographic areas are moving toward poor outcomes, how quickly risk is changing, or which response should follow. Cross-sectional cascades also obscure the longitudinal reality that people move into, out of, and back into care over time.^[6,14] The critical challenge is therefore to move from retrospective measurement of cascade failure toward prospective recognition of cascade vulnerability.

1.3 Aim and contribution of the review

This narrative review re-examines HIV care-cascade failure through that prospective lens. It synthesises evidence on breakdowns from diagnosis to viral suppression, critically evaluates the capacity of surveillance and emerging data-driven approaches to detect vulnerability earlier, and examines how early-warning signals can be translated into timely and targeted intervention. Building on this synthesis, we propose an integrated Surveillance-to-Suppression Framework that links cascade monitoring, risk detection, early warning, targeted response, re-engagement, and viral suppression. This reframing positions the care cascade not simply as a tool for documenting losses after they occur, but as the foundation for a responsive learning system capable of anticipating vulnerability, directing intervention, and using outcomes to strengthen future prevention and care.^[15]

2. Review Approach

We conducted a structured narrative review, an approach suited to integrating heterogeneous conceptual, methodological, and empirical literature and to developing a framework rather than estimating a pooled effect.^[16] The review was designed and reported with reference to the Scale for the Assessment of Narrative Review Articles (SANRA).^[17]

We searched PubMed/MEDLINE, Embase, Scopus, and Web of Science for articles published between January 2010 and August 2026; the final search was conducted on 31 August 2026. Search strings combined terms for

HIV, the care continuum, and surveillance-informed or predictive approaches, for example: "HIV" AND ("care cascade" OR "care continuum" OR "linkage to care" OR "retention in care" OR "re-engagement" OR "viral suppression") AND ("surveillance" OR "Data to Care" OR "cluster detection" OR "early warning" OR "prediction" OR "machine learning"). Searches were limited to English-language publications. We supplemented the database searches with national surveillance reports and public-health guidance from the Centers for Disease Control and Prevention (CDC), the U.S. Department of Health and Human Services, the World Health Organization (WHO), and the Joint United Nations Programme on HIV/AIDS (UNAIDS). We also searched the reference lists of key articles.

We included sources that addressed one or more of the following: mechanisms of care-cascade disruption; HIV surveillance methods and their limitations; the use of surveillance data to guide clinical or public-health action; cluster detection and response; prediction of disengagement or viral non-suppression; interventions to improve linkage, retention, and re-engagement; or the ethics and equity of HIV data use. Priority was given to systematic reviews, randomised and observational studies, national surveillance data, and authoritative guidance. Two authors screened titles and abstracts independently and resolved disagreements through discussion. Evidence was synthesised thematically, and the Surveillance-to-Suppression Framework was developed iteratively from that synthesis. Because this is a narrative review, we did not conduct a formal risk-of-bias assessment or meta-analysis.

3. Where and Why the HIV Care Cascade Breaks Down

HIV care-cascade failure rarely reflects a single point of breakdown. More often, it emerges through interacting clinical, structural, and social vulnerabilities that accumulate over the course of care. A delayed diagnosis can lead to presentation with advanced disease; weak referral pathways can interrupt the transition from testing to treatment; and apparently successful linkage may provide little protection if subsequent engagement is unstable. The cascade should therefore be understood not as a sequence of discrete stages, but as an interconnected process in which vulnerability at one stage can amplify the probability and consequences of failure at those that follow.^[6,13]

3.1 From diagnosis to linkage: the first critical transition

Diagnosis creates an opportunity for treatment, but it does not guarantee entry into sustained care. Late diagnosis may mean that individuals first encounter HIV services after substantial immunological deterioration, which is associated with excess mortality even in the era of effective ART.^[18] Even after diagnosis, the pathway into treatment can be disrupted by fragmented referral systems, appointment delays, transportation difficulties,

unstable housing, stigma, substance use, financial insecurity, and competing demands of employment, caregiving, or basic needs.^[19–21] These barriers frequently coexist rather than operate independently, making the transition from diagnosis to treatment especially vulnerable among socially and economically marginalised populations.

This distinction matters because the conventional cascade can make diagnosis and linkage appear more deterministic than they are. Referral to an HIV clinic is not equivalent to successful integration into care, and attendance at an initial appointment does not necessarily indicate that the conditions for continued treatment have been established. The more important question is not simply whether linkage occurred, but whether the health system converted diagnosis into a durable therapeutic relationship. Rapid or same-day ART initiation illustrates how service design can shorten this vulnerable interval, with evidence of improved viral suppression and retention compared with deferred initiation.^[22–24] From this perspective, early cascade failure reflects not only individual behaviour but also the capacity of health systems to remove barriers between diagnosis and sustained treatment.^[13]

3.2 Retention and re-engagement: the hidden vulnerability of the cascade

The distinction between linkage and retention is particularly important. Linkage is an event; retention is a longitudinal process. A person may successfully initiate care and ART yet subsequently experience missed appointments, interruptions in medication access, relocation, changes in insurance or providers, competing socioeconomic pressures, or disengagement from a fragmented health system. A single documented encounter therefore provides limited information about the stability of a person's longer-term care trajectory.

Retention should be conceptualised as dynamic rather than binary. Individuals may cycle through engagement, interruption, and re-engagement—a pattern described as “churn”—rather than progressing linearly toward sustained viral suppression.^[14,25] This fluidity exposes a weakness in static cascade measurement: aggregate indicators may identify attrition without capturing the trajectories through which it develops. Declining appointment attendance, interrupted ART access, delayed laboratory monitoring, or repeated re-entry into care may signal emerging vulnerability before prolonged disengagement becomes visible in conventional performance measures. Re-engagement is consequently not merely a corrective action after “loss to follow-up”; it is a central component of maintaining continuity across a care pathway in which disengagement may be recurrent.

3.3 Viral non-suppression and advanced HIV disease as downstream manifestations

The consequences of these accumulated disruptions are most visible at the later stages of the cascade. ART

interruption and inconsistent engagement can permit viral rebound, compromise immune recovery, increase the risk of opportunistic illness and other HIV-related morbidity, and undermine the prevention benefits of sustained viral suppression.^[1,3] In more severe cases, advanced HIV disease may be the downstream expression of failures that began considerably earlier in the care trajectory.^[24]

This perspective complicates explanations that locate poor outcomes primarily at the level of individual adherence. Ayo-Ige et al.^[26], reviewing preventable mortality in advanced HIV disease in the universal-ART era, draw attention to persistent gaps in diagnosis, treatment initiation, retention, adherence, and clinical management despite widespread ART availability. Advanced disease and preventable mortality should therefore be interpreted, in appropriate cases, as sentinel outcomes of accumulated system and care-continuity failures rather than isolated clinical events. The same logic applies to persistent viral non-suppression: the final measurable outcome may be biological, but the pathway producing it can be clinical, social, structural, and organisational.

The central challenge is thus temporal as much as clinical. By the time advanced disease, prolonged disengagement, or persistent viral non-suppression is documented, multiple opportunities for earlier intervention may already have been missed. If cascade failures develop progressively rather than suddenly, the critical question becomes whether surveillance systems can detect their emergence before the final adverse outcome occurs.

4. From Cascade Measurement to Actionable Surveillance

If care-cascade failures develop progressively, surveillance should do more than document their eventual consequences. The more consequential question is whether routinely collected HIV data can identify emerging patterns of vulnerability early enough to alter their trajectory. This requires a conceptual shift from surveillance as a largely descriptive function toward actionable surveillance: the systematic use of timely, integrated data not only to characterise population outcomes, but also to identify where intervention is becoming necessary, determine the appropriate level of response, and assess whether that response changes subsequent outcomes.^[27]

4.1 What conventional HIV surveillance tells us—and what it does not

Contemporary HIV surveillance provides an indispensable epidemiological infrastructure for monitoring the continuum of care. New diagnoses, CD4 measurements, viral-load results, linkage, retention, and viral suppression together reveal where progress is being achieved and where losses persist. In U.S. national surveillance, linkage is operationalised through

documented CD4 or viral-load testing after diagnosis, and retention and viral suppression are derived from subsequent laboratory evidence.^[7] These measures permit standardised assessment of outcomes across populations and jurisdictions and remain essential for programme planning and accountability.

Yet measurement is not synonymous with situational awareness. Surveillance indicators are constrained by the systems that generate them. Reporting delays, incomplete laboratory or clinical information, movement across jurisdictions, and limited interoperability between surveillance, clinical, pharmacy, and social-service data can produce an incomplete representation of a person's actual care trajectory. Indicator definitions also shape what is interpreted as successful engagement. Laboratory-based proxies for retention capture an observable component of care and correlate reasonably with clinic attendance^[28], but they cannot fully represent medication continuity, the quality of clinical engagement, or the social circumstances influencing a person's ability to remain in treatment. Conventional surveillance is therefore strongest at answering what has been observed, and considerably less informative about why deterioration is occurring and what is likely to happen next.

4.2 Using surveillance data to act: lessons from Data to Care

Data to Care strategies, in which health departments use surveillance laboratory data to identify people who appear to be out of care and then support re-engagement, represent the most established attempt to convert HIV surveillance into individual-level action.^[27] Their evaluation offers important lessons. Clinic- and health-department-based relinkage efforts have found that a substantial proportion of people classified as out of care had in fact relocated or were receiving care elsewhere, revealing the limits of surveillance data completeness.^[29] A cluster randomised evaluation of a health-department Data to Care intervention did not demonstrate a significant improvement in engagement or viral suppression over usual practice.^[30] These findings do not negate the value of surveillance-informed response, but they show that identification alone is insufficient: the accuracy of the signal, the timeliness of outreach, and the effectiveness of the subsequent intervention jointly determine impact.

4.3 Detecting population and geographic disparities

The value of surveillance becomes particularly evident when individual observations are aggregated to reveal patterned inequalities. Geographic differences in late diagnosis, linkage, retention, or viral suppression can identify communities in which poor outcomes are concentrated rather than randomly distributed. Stratification by demographic and epidemiological characteristics can similarly reveal populations for whom aggregate improvements conceal persistent disadvantage.^[7]

Ayo-Ige and Botwe^[31], examining HIV surveillance in underserved U.S. communities, situate emerging epidemiological and data-driven approaches within this broader need to identify populations insufficiently reached by existing systems. Importantly, surveillance inequity can reproduce healthcare inequity. Communities with limited testing, fragmented healthcare access, inconsistent laboratory monitoring, or weak reporting infrastructure may generate less complete data precisely because they are underserved. The apparent absence of a surveillance signal must therefore not be equated with the absence of need. Actionable surveillance requires attention not only to where adverse outcomes are observed, but also to where the information needed to observe them is systematically incomplete.

4.4 Cluster detection as a model for moving from surveillance to response

HIV cluster detection and response (CDR) provides an instructive model for closing the gap between epidemiological observation and public-health action. The 2014–2015 outbreak among people who inject drugs in Scott County, Indiana, demonstrated the cost of delayed recognition and the value of rapid, coordinated response.^[32] Analysis of molecular surveillance data subsequently made it possible to identify clusters of recent and rapid transmission systematically.^[33] Rather than treating surveillance as an endpoint, CDR uses surveillance and complementary information to identify communities experiencing rapid transmission, investigate underlying prevention and care gaps, prioritise concern, and tailor responses across individual, network, and system levels.^[34] Ayo-Ige and Botwe^[35] similarly emphasise translating cluster detection into rapid, coordinated response rather than allowing identification itself to become the principal measure of surveillance success.

The significance of this model extends beyond transmission clusters. Its underlying logic detect an abnormal pattern, contextualise the signal, assess urgency, mobilise an appropriate response, and continue monitoring offers a potentially valuable template for addressing failures within the care continuum. Repeated care interruptions, localised declines in viral suppression, or concentrations of disengagement within particular populations may likewise warrant investigation before they become entrenched patterns of morbidity or transmission risk. This does not imply that transmission clusters and care disengagement are epidemiologically equivalent, nor that molecular CDR methods should simply be repurposed for retention monitoring. The transferable principle is organisational: surveillance becomes more consequential when predefined signals initiate investigation and proportionate action.

The question is therefore no longer simply whether HIV programmes can measure cascade failure more precisely.

It is whether the response-oriented logic of cluster detection can be extended to recognise emerging disengagement and viral non-suppression early enough to change their course. Answering that question requires an early-warning architecture capable of distinguishing routine variation from signals that warrant intervention.

5. Building an Early-Warning System for Care-Cascade Failure

If actionable surveillance is intended to identify cascade vulnerability before poor outcomes become entrenched, the central challenge is to determine what constitutes a meaningful early-warning signal and how such signals should trigger intervention. This requires more than increasing the volume of data collected. An effective early-warning system must distinguish ordinary fluctuations in engagement from patterns that plausibly indicate increasing risk, combine information generated at different points in the health system, and connect detection to a defined response. Its purpose is not simply to predict failure, but to create sufficient lead time for failure to be prevented or mitigated.

5.1 From retrospective indicators to prospective risk signals

Four related functions should be distinguished. *Monitoring* asks what has already happened; *early warning* asks where deterioration may be beginning; *prediction* estimates which individuals or populations face an elevated probability of a subsequent adverse outcome; and *response* determines what should be done once a concerning signal has been identified. Collapsing these functions into a single concept risks overstating what surveillance or predictive analytics can accomplish. A model may classify risk accurately without revealing why that risk exists, whether it is modifiable, or which intervention is appropriate.

Potential warning signals exist throughout the care trajectory (Table 1). Repeated missed appointments, delayed laboratory monitoring, detectable or rising viral load, interruptions in ART access, late medication refills, previous episodes of disengagement, repeated re-entry into care, and abrupt changes in care location may indicate emerging instability.^[20,25] At the population level, unusual geographic concentrations of viral non-suppression or care interruption could similarly warrant investigation. These signals should not, however, be treated as interchangeable or assumed to have equivalent predictive validity. Some directly reflect treatment interruption, whereas others are proxies for broader instability. Their significance also depends on timing, frequency, baseline history, and clinical and social context. Early-warning systems therefore require validated thresholds and longitudinal interpretation rather than indiscriminate flagging of every deviation from expected care.

Table 1: Illustrative early-warning signals across the HIV care continuum, their data sources, and proportionate responses.

Cascade stage	Candidate early-warning signal	Principal data source(s)	Level	Proportionate response (examples)
Diagnosis → linkage	No CD4 or viral-load result within 30 days of diagnosis; low CD4 at diagnosis.	Surveillance laboratory reporting; testing programme records	Individual	Rapid or same-day ART; linkage navigation; advanced-disease assessment
Linkage → retention	Missed first or second scheduled visit; no-show pattern after ART start	EHR scheduling data	Individual	Navigator or peer contact; telehealth; transport and scheduling support
Retention	Overdue laboratory monitoring; gap in visits exceeding programme threshold	EHR; surveillance laboratory data	Individual	Enhanced personal contact; case management; verify relocation or care elsewhere
Treatment continuity	Late or missed ART refills; insurance or coverage lapse	Pharmacy/claims data; benefits systems	Individual / system	Adherence support; benefits navigation; medication access assistance
Viral suppression	Detectable or rising viral load after prior suppression	Laboratory data; surveillance	Individual	Clinical review; adherence and social-needs assessment; resistance testing where indicated
Re-engagement	Repeated cycles of disengagement and re-entry (“churn”)	Longitudinal EHR and surveillance linkage	Individual / network	Intensive case management; address structural drivers (e.g., housing)
Population	Geographic or population concentration of non-suppression or care interruption	Aggregated surveillance; geospatial data	Community/system	Community partnership; mobile services; resource redistribution; programme review

Note. Signals are illustrative and require local validation of thresholds, predictive value, and lead time before operational use. ART = antiretroviral therapy; EHR = electronic health record.

5.2 Integrating multiple data streams

The limitations of any single indicator provide a strong rationale for data integration. Electronic health records characterise clinical encounters and laboratory trajectories; surveillance systems provide population-level information on diagnoses and viral-load patterns; pharmacy or refill data may indicate continuity of ART access; and social or structural information can provide context for risks that clinical data alone cannot explain. Geographic and network information may further reveal concentrations of vulnerability that are difficult to detect through individual records.

The theoretical advantage is a more complete representation of the trajectory between engagement and disengagement. The practical difficulty is that these data are rarely generated within a single interoperable system. Differences in reporting boundaries, identifiers, data standards, jurisdictional boundaries, missingness, and institutional access can undermine the timeliness and interpretability of integrated signals.^[29] More importantly, data completeness is itself socially patterned. People with unstable healthcare access or limited contact with formal services leave fewer observable data points and can consequently become less visible to precisely the systems intended to identify vulnerability. Predictive systems trained on routinely observed populations may therefore perform poorly among groups whose care is fragmented or under-recorded.

Integration also creates ethical obligations. Combining clinical, surveillance, pharmacy, social, geographic, and network information increases analytical power, but it also increases the sensitivity of the resulting data architecture.^[36] Privacy protection, data minimisation, transparent governance, appropriate access controls, and meaningful community engagement should therefore be treated as design requirements rather than secondary considerations.

5.3 Mathematical modelling and predictive analytics

Mathematical modelling and predictive analytics could extend this architecture by transforming longitudinal observations into estimates of changing risk. Lawal et al.^[37] argue for a more responsive and integrated role for mathematical modelling in infectious-disease epidemiology, moving beyond retrospective explanation toward models capable of informing adaptive public-health decision-making. Empirical work supports the feasibility of this approach in HIV care: machine-learning models using routine clinical data have predicted missed visits in a U.S. urban HIV clinic^[38] and both retention and viral suppression in large South African treatment cohorts.^[39] Applied to the care cascade, such approaches could help identify changing patterns of disengagement, estimate trajectories toward viral non-suppression, prioritise populations or settings for closer investigation, compare intervention scenarios, and allocate limited outreach resources more efficiently.

Yet predictive performance should not be confused with public-health effectiveness. A model with strong statistical discrimination may still have limited clinical value if its inputs are delayed, its predictions are poorly calibrated across populations^[40], its risk categories are not interpretable to practitioners, or no feasible intervention follows a high-risk designation. False-positive classifications may consume scarce resources or intensify unnecessary surveillance, whereas false negatives may provide false reassurance and leave vulnerable people without support. These concerns are particularly important when models are developed from historical data that encode existing disparities in access, engagement, and documentation; an algorithm that uses a biased proxy as its target can systematically under-identify need in disadvantaged groups.^[41] Transparent development, external validation, and reporting consistent with the TRIPOD+AI statement should therefore be minimum requirements before deployment.^[42]

The appropriate endpoint for an early-warning system is therefore not predictive accuracy alone, but actionability: whether a sufficiently reliable signal arrives early enough, identifies a potentially modifiable risk, and activates an intervention capable of improving the subsequent care trajectory. This reframes modelling as one component of a broader learning system rather than the endpoint of surveillance innovation. Prediction without an intervention pathway risks becoming sophisticated surveillance without improved care. The next question is how different warning signals can be matched to interventions of appropriate intensity, timing, and scale.

6. From Early Warning to Targeted Intervention

An early-warning system has limited value if identifying risk does not alter the subsequent course of care. The practical challenge is to translate surveillance signals into interventions that are timely, proportionate, and responsive to the mechanism producing vulnerability. This requires moving beyond a uniform model of HIV service delivery toward a signal-to-response approach, in which the nature and intensity of intervention change as evidence of cascade instability accumulates. The objective is not to intervene maximally in every case, but to intervene early enough and at the appropriate level to prevent transient vulnerability from progressing to sustained disengagement or viral non-suppression.

6.1 Matching intervention intensity to detected risk

The appropriate response depends first on where and how vulnerability is detected (Table 1). A new HIV diagnosis requires rapid linkage and timely ART initiation.^[22,24] An early indication of declining engagement may warrant patient navigation, peer support, telehealth contact, transportation assistance, or resolution of emerging access barriers; patient navigation has been associated with improved linkage, retention, and viral suppression^[43], and low-intensity enhanced

personal contact has improved retention in a multisite U.S. trial.^[44] Repeated missed care or treatment interruption signals a different level of concern and may justify intensified outreach, case management, and active re-engagement.^[45] Viral rebound requires clinical assessment alongside evaluation of adherence, treatment access, drug resistance where appropriate, and the social circumstances affecting continuity of ART. When deterioration is concentrated geographically or within particular networks or populations, individual outreach alone may be insufficient; community partnerships, mobile services, expanded testing and treatment access, or redistribution of programme resources may be necessary.

The central principle is response proportionality. Risk should not merely be classified; it should be linked to a predefined range of actions whose intensity can escalate or de-escalate as circumstances change. This approach is consistent with the logic of the U.S. Ending the HIV Epidemic initiative and its Diagnose, Treat, Prevent, and Respond pillars, which connect timely diagnosis and treatment with data-informed responses to emerging transmission.^[10,46] The relevant extension for the care cascade is to apply similarly responsive thinking to emerging patterns of disengagement and viral non-suppression.

6.2 Individual, network, and system-level intervention

A risk-stratified approach must also avoid locating every failure within the individual. Missed appointments and treatment interruptions are observable at the patient level, but their causes may originate elsewhere. A person repeatedly unable to attend care because of transportation barriers requires a different response from someone whose interruption follows an unprocessed referral, loss of insurance coverage, poor transfer of records, or limited local service availability. Treating each scenario primarily as “non-adherence” risks converting health-system deficiencies into patient-level explanations and reinforcing stigma.^[21]

Interventions should therefore operate across multiple levels. At the individual level, navigation, adherence support, case management, peer support, and re-engagement services can address immediate barriers to continuity. At the network and community level, trusted community organisations, outreach programmes, mobile services, and locally tailored interventions can reach populations poorly served by conventional facility-based care. At the system level, interoperable records, automated referral and follow-up processes, surveillance-to-care workflows, and strategic redistribution of resources can address failures generated by fragmented service delivery, including structural determinants such as housing instability.^[19] These levels are complementary: an individual alert may reveal a system problem, while repeated individual alerts may constitute a population-level signal requiring structural intervention.

6.3 Equity and ethics of targeted surveillance

Greater capacity to identify vulnerability creates greater responsibility in how that information is used. Systems combining clinical, surveillance, geographic, behavioural, or network data raise legitimate concerns about privacy, confidentiality, stigma, algorithmic bias, community trust, and the potential misuse of sensitive HIV information.^[36,41] These concerns are particularly consequential where HIV exposure or transmission may intersect with criminal law, or where marginalised communities have historical reasons to distrust surveillance institutions.

Equity therefore cannot be reduced to achieving similar predictive accuracy across demographic groups. It also requires asking whether people identified as high risk receive meaningful additional support, and whether communities generating surveillance signals receive additional resources rather than additional scrutiny alone. A system that becomes increasingly capable of identifying vulnerability while leaving the underlying barriers to care unchanged may intensify surveillance without improving health. The success of targeted intervention should be judged not by the number of alerts generated or people classified as high risk, but by whether those signals produce earlier, acceptable, and effective support. The ethical justification for more intelligent surveillance ultimately rests on its capacity to produce more responsive care.

7. An Integrated Surveillance-to-Suppression Framework

The preceding evidence suggests that the conventional HIV care cascade remains essential for measuring progress, but its linear structure does not fully capture the dynamic processes through which disengagement develops, risk changes over time, and people move into, out of, and back into care. We therefore propose an integrated Surveillance-to-Suppression Framework that reconceptualises the cascade as a continuous learning system organised around seven interconnected functions:

Detect, Anticipate, Triage, Intervene, Re-engage, Suppress, and Learn (Figure 1; Table 2). The framework is not intended to replace established care-continuum indicators. Rather, it extends their utility by connecting measurement explicitly to early recognition and response.

Detect establishes a person's current position within the care continuum, including diagnosis, linkage, treatment engagement, and virological status. *Anticipate* shifts attention from current status to trajectory by identifying credible signals of emerging disengagement, treatment interruption, or viral non-suppression. *Triage* translates those signals into decisions about urgency, modifiability, and the appropriate intensity and level of response. *Intervene* connects identified need with individual-, network-, community-, or system-level support rather than assuming that every detected failure requires the same intervention. *Re-engage* recognises that movement through HIV care is not invariably linear, and that treatment interruption should initiate active pathways back into care rather than represent an endpoint of the cascade. *Suppress* retains sustained viral suppression as the principal therapeutic objective while recognising that achieving it depends on continuity across the preceding functions.

The final function, *Learn*, distinguishes the framework from a conventional linear cascade. Outcomes after intervention should return to the surveillance system: Was re-engagement achieved? Was ART initiated or restored? Was viral suppression attained and sustained? Which intervention worked, for whom, under what circumstances, and how quickly? This feedback allows detection thresholds, triage decisions, intervention strategies, and resource allocation to be refined as evidence accumulates—the defining feature of a learning health system.^[15] The framework therefore operates as a cycle: surveillance → early warning → targeted intervention → outcome assessment → surveillance and learning.

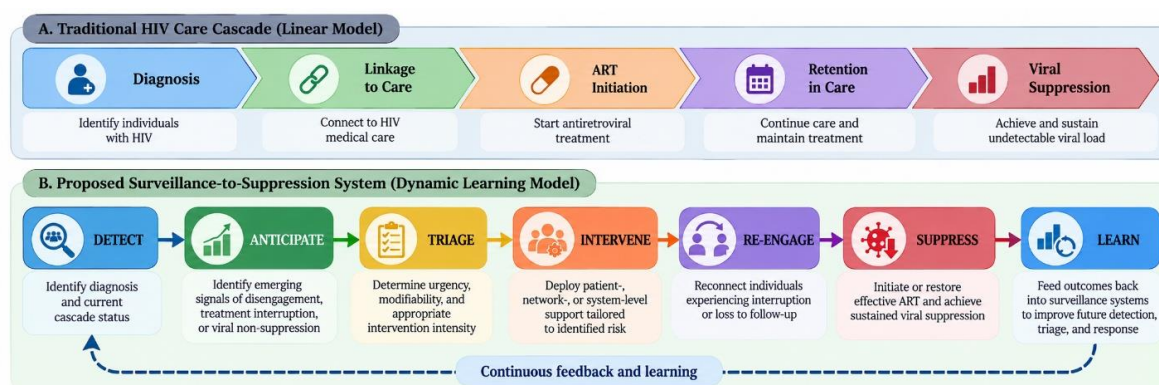


Figure 1: From a linear HIV care cascade to a responsive Surveillance-to-Suppression system. The upper panel depicts the conventional HIV care cascade as a linear progression from diagnosis through linkage to care, ART initiation, retention, and viral suppression. The lower panel presents the proposed Surveillance-to-Suppression Framework, comprising seven interconnected functions: Detect, Anticipate, Triage, Intervene, Re-engage, Suppress, and Learn. Unlike the linear model, the framework incorporates a continuous feedback loop through

which intervention outcomes and evolving surveillance information inform subsequent detection, risk assessment, triage, and response. ART = antiretroviral therapy.

Table 2: Functions of the Surveillance-to-Suppression Framework.

Function	Core question	Key inputs	Illustrative outputs and metrics
Detect	Where is this person or population in the care continuum now?	Diagnoses; CD4 and viral-load results; visit and ART records	Current cascade status; data-completeness flags
Anticipate	Is the trajectory deteriorating?	Longitudinal visit, refill, and laboratory patterns; validated risk models	Calibrated risk estimate; signal with lead time
Triage	How urgent and modifiable is the risk, and at what level?	Risk signal; clinical and social context; service capacity	Assigned response tier and responsible team
Intervene	Which response matches the mechanism of risk?	Triage decision; available individual, community, and system services	Intervention delivered; time from signal to action
Re-engage	Has the person returned to care after interruption?	Outreach records; subsequent visits and laboratory results	Re-engagement rate; time to return
Suppress	Is viral suppression achieved and sustained?	Viral-load results over time	Suppression and durable-suppression rates
Learn	What worked, for whom, and how quickly?	Linked signal, intervention, and outcome data	Refined thresholds, models, triage rules, and resource allocation; equity audit

Note. Functions are interdependent and iterative; outputs of Learn feed back into Detect and Anticipate.

The central proposition is that HIV programmes should not have to wait for prolonged disengagement or persistent viral non-suppression before recognising that a care trajectory is deteriorating. The objective is to create an actionable interval between the earliest credible indication of vulnerability and the eventual adverse outcome. The framework does not assume that every warning signal warrants intensive intervention or that prediction itself improves care. Its value depends on accurate and equitable detection, proportionate responses, adequate service capacity, and continuous evaluation of whether intervention actually changes outcomes. Reframed in this way, the HIV care cascade becomes not merely a retrospective account of who reached viral suppression, but a responsive learning architecture designed to prevent avoidable losses before they become established failures.

8. Evidence Gaps and Research Priorities

Moving from retrospective cascade measurement to anticipatory intervention exposes several unresolved questions that should define the next phase of research. Foremost is the need to establish which routinely observable signals provide sufficiently early and reliable indications of subsequent disengagement or viral non-suppression. Missed appointments, delayed laboratory monitoring, ART refill gaps, previous interruptions in care, and changing viral-load trajectories are plausible indicators, but their predictive value, optimal combinations, and appropriate thresholds require validation across populations and care settings. Research should prioritise actionable lead time whether a signal becomes informative early enough for intervention to alter the trajectory rather than predictive accuracy alone.

A second priority is demonstrating clinical and public-health utility. Much predictive research is evaluated through statistical performance, yet discrimination, calibration, or classification accuracy does not establish that implementation improves retention, shortens treatment interruptions, increases viral suppression, or reduces morbidity.^[40,42] The mixed results of surveillance-based relinkage^[30] underscore this point. Prospective and pragmatic implementation studies, including cluster randomised and stepped-wedge designs, should compare prediction-linked interventions with existing approaches and determine whether risk-stratified responses outperform uniform service delivery.

The underlying data architecture presents an equally important research problem. Clinical, laboratory, pharmacy, surveillance, and social data frequently reside in systems developed for different purposes and governed by different institutions. Research is needed on interoperable models that generate timely signals while maintaining confidentiality, limiting unnecessary data exchange, and preserving public trust.^[36] This challenge is inseparable from equity. Predictive performance should be evaluated across populations with differing healthcare access and data completeness, because people with fragmented care may simultaneously face greater vulnerability and generate fewer observable data.

Finally, intervention research must determine which response works for which signal, for whom, and under what circumstances. Particular attention is needed in rural and underserved communities, where identifying elevated risk may have little practical value if navigation, specialist care, transportation, or re-engagement services are unavailable.^[31] Cross-sector collaboration may help address such constraints; broader global-health

scholarship, including Nwokedi et al.^[47], illustrates the importance of coordinated partnerships when health problems span institutional and sectoral boundaries. For HIV care, however, this principle requires direct empirical testing. The research agenda must move beyond asking whether cascade failure can be predicted toward determining whether prediction can be translated into earlier, equitable, and measurably better care.

9. Public Health and Policy Implications

A surveillance-to-suppression approach would change how HIV surveillance performance is judged. Systems should continue to measure diagnoses, linkage, retention, and viral suppression, but their public-health value should increasingly include whether they generate sufficiently timely information to alter care trajectories. The relevant question is not simply how accurately a system counts adverse outcomes, but whether the information it produces enables preventable adverse outcomes to be avoided.

Operationalising this principle requires stronger connections between surveillance and service delivery. Clinical, laboratory, and public-health information systems need sufficient interoperability to identify meaningful changes in care trajectories without creating indiscriminate data sharing. Equally important are explicit signal-to-action protocols defining who reviews an alert, how urgency is assessed, which services can be activated, and how outcomes are returned to the system. Without such mechanisms, increasingly sophisticated surveillance may identify vulnerability while leaving responsibility for responding to it unclear.

Current U.S. cluster detection and response guidance provides an important precedent. It emphasises integrating multiple sources of information, identifying gaps in prevention and care, engaging affected communities, and tailoring responses at individual, network, and system levels.^[34] The Surveillance-to-Suppression Framework extends this response-oriented logic from detecting rapid transmission toward identifying emerging failure within the care continuum.^[35]

Implementation must nevertheless be locally responsive. Underserved communities require investment not only in surveillance infrastructure but also in the services required to act on surveillance findings.^[31] Generating increasingly precise signals of disengagement where navigation, transportation, treatment access, or re-engagement capacity remains inadequate would expose need without resolving it. Policy should therefore align investment in detection capacity with investment in response capacity, while embedding confidentiality safeguards, community engagement, and equity assessment throughout implementation. The ultimate measure of an actionable surveillance system is not how much it knows about vulnerability, but whether that knowledge produces earlier and more effective care.

10. Strengths and Limitations

This review integrates evidence from clinical epidemiology, public-health surveillance, implementation science, predictive analytics, and ethics to offer a framework that is both conceptually grounded and operationally specific. Several limitations should be acknowledged. As a narrative rather than systematic review, it may be subject to selection bias, and it does not provide pooled effect estimates. The evidence base draws heavily on U.S. surveillance systems and guidance, and transferability to settings with different health-system architectures, data infrastructures, and legal environments requires examination. Finally, the Surveillance-to-Suppression Framework is a conceptual proposal; its components are supported by existing evidence, but the integrated framework has not been prospectively evaluated, and its feasibility, cost-effectiveness, and acceptability to people living with HIV remain to be established.

11. CONCLUSION

The persistence of care-cascade failures despite highly effective ART suggests that the next advance in HIV control will depend not only on improving treatment, but also on improving how health systems recognise and respond to deteriorating care trajectories. The conventional cascade has been indispensable for revealing where losses occur between diagnosis and viral suppression. The challenge now is to complement that retrospective function with the capacity to identify vulnerability while there is still time to intervene.

The central question should therefore evolve from “Where are people being lost?” to “Can impending disengagement be recognised early enough to prevent it?” Surveillance, integrated data systems, predictive analytics, and mathematical modelling can contribute to that transition, but none is an endpoint in itself. Their value depends on whether credible signals lead to timely, proportionate, equitable, and effective responses.

The proposed Surveillance-to-Suppression Framework accordingly reframes the cascade as a continuous cycle of detection, anticipation, triage, intervention, re-engagement, suppression, and learning. Its premise is straightforward: information becomes consequential when it changes care. The future of the HIV care cascade may lie not in measuring failure more precisely after it occurs, but in building learning health systems capable of anticipating failure, intervening early, and continuously adapting until sustained viral suppression is achieved.

Declarations

Author Contributions (CRediT)

Jane Ifeyinwa Anatuanya: Conceptualization, Methodology, Investigation, Literature Review, Writing – Original Draft, Writing – Review & Editing, Visualization, and Project Administration.

Ndubisi Ubaka Edebeatu: Methodology, Investigation, Literature Review, Writing – Original Draft, Writing – Review & Editing, and Validation.

Ogechi Njoku: Investigation, Literature Review, Writing – Original Draft, Writing – Review & Editing, and Validation.

All authors contributed to the intellectual development of the manuscript, critically reviewed the manuscript for important intellectual content, approved the final version, and agreed to be accountable for the work.

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