REVIEW

Indonesian Journal of Blood and Transfusion (*IDJBT*) 2026, Volume 4, Number 2: 31-37

Chemiluminescence immunoassay and nucleic acid testing for TTI screening: A narrative review of performance, complementarity, and blood safety

PUBLISHED BY
THE INDONESIAN SOCIETY BLOOD TRANSFUSION PHYSICIAN

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Received: 2026-09-16
Accepted: 2026-10-14
Published: 2026-11-01

ABSTRACT

Introduction: Screening for transfusion-transmitted infections (TTIs) is essential to blood safety. Chemiluminescence immunoassay (ChLIA) enables automated, high-throughput serological screening, whereas nucleic acid testing (NAT) detects viral nucleic acids and reduces the diagnostic window period. This review aimed to evaluate ChLIA for screening hepatitis B virus (HBV), hepatitis C virus (HCV), human immunodeficiency virus (HIV), and syphilis; compare its performance with NAT for HBV, HCV, and HIV; and examine the implications for transfusion safety.

Methods: A directed narrative review was conducted by a single reviewer (A.K.). PubMed was searched on September 7, 2026, using a predefined, reproducible search strategy. Supplementary searches included peer-reviewed journals, reference lists, World Health Organization publications, and official Indonesian regulatory sources. Studies were prioritized according to their relevance to blood donor screening, ChLIA–NAT comparisons, residual transfusion risk, occult HBV infection, and Indonesian regulatory requirements. Uncertain records underwent full-text assessment.

Results: The included studies varied in assay characteristics, screening markers, donor populations, and reference standards, precluding meaningful pooling or generalization of diagnostic accuracy estimates. ChLIA and NAT detect distinct biological targets, with their relative contributions to blood safety influenced by pathogen epidemiology, residual risk, regulatory requirements, and healthcare resources. Findings from Shahin et al. and the Indonesian study are presented with their respective denominators and discordant testing patterns to ensure appropriate interpretation.

Conclusion: ChLIA demonstrates high diagnostic performance, although accuracy varies across assays and clinical settings. Its complementary use with NAT may enhance transfusion safety when guided by pathogen-specific residual risk, local epidemiology, regulatory requirements, and healthcare capacity. Both approaches should be integrated within comprehensive quality assurance and hemovigilance systems.

Keywords: blood donors, hepatitis B, hepatitis C, HIV infections, serologic tests.
Cite This Article: Karim, A. 2026. Chemiluminescence immunoassay and nucleic acid testing for TTI screening: A narrative review of performance, complementarity, and blood safety. *Indonesian Journal of Blood and Transfusion.* 4(2): 31-37

INTRODUCTION

Transfusion safety relies on coordinated processes encompassing donor selection, blood collection, infectious disease screening, component processing, storage, distribution, transfusion, and hemovigilance. Although analytical sensitivity and specificity characterize diagnostic test performance, they do not independently establish clinical effectiveness or transfusion safety. These outcomes also depend on infection incidence, window-period risk, confirmatory testing, blood component management, donor follow-up, traceability, and quality assurance.[1] In Indonesia, the current regulatory designation for blood establishments is Unit Pengelola Darah (UPD), replacing the terminology Unit Transfusi Darah (UTD) used in earlier regulations. Minister of Health Regulation No. 11 of 2025 establishes the current UPD licensing and service framework, while Minister of Health Regulation No. 91 of 2015 provides technical standards for blood services. Additionally, BPOM Regulation No. 11 of 2025 governs good manufacturing practices for UPDs and blood plasma banks, including quality management, traceability, and recall procedures. These regulations underscore the importance of evaluating screening technologies in relation to residual infection risk, donor management, blood component wastage, and safe component release.[2–4]

Chemiluminescence immunoassay (ChLIA) and nucleic acid testing (NAT) detect different biological markers.

ChLIA identifies antigens and/or antibodies, whereas NAT detects viral nucleic acids. Agreement between these methods is influenced by infection stage, viral replication, seroconversion, assay characteristics, and donor epidemiology. Despite substantial evidence on both technologies, interpreting heterogeneous diagnostic performance remains challenging, particularly when NAT is treated as a universal reference standard or analytical accuracy is assumed to reflect reductions in transfusion-transmitted infections directly.[5]

This narrative review evaluates ChLIA-based screening for hepatitis B virus (HBV), hepatitis C virus (HCV), human immunodeficiency virus (HIV), and syphilis; compares ChLIA and NAT findings for HBV, HCV, and HIV; and examines their implications for residual risk, donor management, blood component wastage, and Indonesian UPD regulations. Formal comparative effectiveness and cost-effectiveness analyses are beyond the scope of this review.

METHODS

The literature search was conducted by a single reviewer (A.K.), with the final search performed on September 7, 2026. PubMed was searched using the following strategy: ((chemiluminescence OR chemiluminescent OR CLIA OR ChLIA OR ECLIA) AND (blood donor* OR blood donation OR transfusion) AND (screen* OR transfusion-transmitted infection* OR TTI) AND (HBV OR hepatitis B OR HCV OR hepatitis C OR HIV OR syphilis OR Treponema pallidum OR nucleic acid test* OR NAT OR occult hepatitis B OR window period OR residual risk)). No language restrictions were applied. Supplementary searches were conducted through peer-reviewed journal websites, reference lists of included studies, World Health Organization (WHO) resources, and official Indonesian regulatory and health-authority websites using relevant search terms and document titles.

Titles and abstracts were screened for relevance to blood donor screening, followed by full-text assessment of potentially eligible records. Priority was given to official guidelines and regulations, donor-based studies, reports providing marker-specific denominators or discordant findings, direct serology–NAT comparisons, evidence on residual transfusion risk and occult hepatitis B virus infection, and Indonesian studies. Patient-based diagnostic studies without clear implications for donor screening, duplicate publications, unsupported opinion articles, and reports with insufficient methodological detail were excluded from the primary evidence synthesis. Uncertain records were reassessed through full-text review and retained only when relevant to predefined review domains. All screening decisions were made by the same reviewer. Given its directed narrative design, this review did not employ a systematic multi-database search, duplicate screening, formal risk-of-bias assessment, meta-analysis, or PRISMA flow diagram. Evidence was synthesized qualitatively according to its relevance to donor screening, source type, methodological transparency, biological plausibility, consistency, and applicability to transfusion practice. Ethical approval and informed consent were not applicable because the review exclusively analyzed published literature and publicly available documents without involving human participants, identifiable personal data, interventions, or new biological specimen collection.

RESULTS AND DISCUSSION

Biological basis of ChLIA and NAT in TTI screening

Chemiluminescence immunoassay (ChLIA) detects antigen–antibody interactions through measurable light signals. In blood donor screening, its primary targets include hepatitis B surface antigen (HBsAg), anti-hepatitis C virus (anti-HCV) antibodies, combined human immunodeficiency virus (HIV) antigen/antibody markers, and antibodies against *Treponema pallidum*. Automated ChLIA platforms minimize operator-dependent variability, enable high-throughput testing, and facilitate integration with laboratory information systems. Combined antigen/antibody assays may shorten the serological window period compared with antibody-only assays, although detection remains dependent on the presence of target biomarkers at detectable concentrations.[6–9]

Nucleic acid testing (NAT) detects viral DNA or RNA through nucleic acid amplification, enabling earlier identification of certain infections before serological markers become detectable. NAT may be performed using individual-donation NAT (ID-NAT) or minipool NAT (MP-NAT), with detection sensitivity influenced by the assay's limit of detection, sample volume, pool size, and testing algorithms. This review compares ChLIA and NAT for hepatitis B virus (HBV), hepatitis C virus (HCV), and HIV, while syphilis screening is evaluated exclusively within the serological ChLIA framework.[10,11] Table 1 summarizes the key characteristics of ChLIA and NAT in blood donor screening.

Screening performance of ChLIA in donor populations

The diagnostic performance of chemiluminescence immunoassay (ChLIA) varies according to the target marker, assay generation, analytical sensitivity, infection prevalence, sample composition, genotype distribution, viral variants, donor characteristics, and reference standard. Reports of 100% sensitivity or specificity should therefore be interpreted in relation to sample size, confidence intervals, validation panels, and intended clinical application rather than as evidence of absolute diagnostic accuracy.

Shahin et al. evaluated 87,620 blood donations using ChLIA and individual-donation nucleic acid testing (ID-NAT), with NAT serving as the study-defined comparator. For hepatitis B virus (HBV), the reported classifications comprised 589 true-positive, 87 false-positive, 32 false-negative, and 86,912 true-negative results. The corresponding values were 1,305, 172, 23, and 86,120 for hepatitis C virus (HCV), and 19, 3, 0, and 87,598 for human immunodeficiency virus (HIV). The investigators reported sensitivities and specificities of 94.85% and 99.90% for HBV, 98.27% and 99.80% for HCV, and 100% and approximately 100% for HIV, respectively. These estimates were adopted directly from the original study without recalculation. Importantly, they represent agreement with the study-defined NAT comparator rather than absolute diagnostic

accuracy. Serology-positive/NAT-negative findings may reflect persistent antibodies, resolved infection, or intermittent or low-level viremia and should not automatically be classified as false-positive results.[5]

Additional blood donor studies have demonstrated high but assay-dependent diagnostic performance. Tiwari et al. evaluated 10,164 donors and reported Enhanced Chemiluminescence Immunoassay (ECLIA) sensitivity of 100% for HBV, HCV, and HIV, with specificity ranging from 99.62% to 99.97%. Arcot et al., in a study involving 4,843 donors, reported sensitivity of 94.9% for HBV and 100% for HCV, HIV, and syphilis, with specificity ranging from 99.8% to 99.9%. Similarly, a Polish evaluation of the Alinity systems demonstrated 100% sensitivity and 99.92%–100% specificity during pre-implementation assessment, with comparable findings subsequently observed in approximately 150,000 routine blood donations.[7,9,12]

Evidence from Indonesia further supports the applicability of chemiluminescence-based donor screening. An evaluation conducted at the Central Blood Transfusion Services of the Indonesian Red Cross reported sensitivity and specificity of 100% and 100% for hepatitis B surface antigen (HBsAg), 100% and 99.8% for anti-HCV, and 100% and 100% for syphilis, respectively. However, these findings were presented as a conference poster abstract and reflect the performance of a specific platform, limiting their generalizability.[13] **Table 2** summarizes selected studies evaluating chemiluminescence-based screening performance among blood donors.

ChLIA and NAT for HBV, HCV, and HIV: complementarity rather than dichotomy

Chemiluminescence immunoassay (ChLIA) and nucleic acid testing (NAT) should be regarded as complementary rather than hierarchically superior screening methods. Although NAT can detect early viremia before serological markers become detectable, it neither eliminates residual transfusion risk nor identifies all clinically relevant serological states. The additional benefit of NAT depends on pathogen epidemiology, assay detection limits, individual-donation versus minipool testing configurations, residual infection risk, regulatory requirements, confirmatory testing capacity, and available resources.

Table 1. Conceptual comparison of ChLIA and NAT in blood-donor screening

Domain	ChLIA/CLIA	NAT	Transfusion-medicine implication
Biological target	Antigen and/or antibody	Viral DNA/RNA	Methods detect different biological phases and are not interchangeable.
Window period	Longer for some infections	Generally shorter for viral markers	NAT may identify some seronegative window-period donations.
Throughput	High; strong automation	High, but molecular workflow is more complex	Both can support large volumes with different infrastructure needs.
False-reactive mechanisms	Interference and non-specific reactivity	Contamination or non-specific amplification may occur	Resolution algorithms are required to avoid unnecessary deferral/discard.
Primary role	Routine serological TTI screening	Additional molecular layer for HBV/HCV/HIV	Use should follow epidemiology, regulation, residual risk, and resources.

NAT comparison in this review applies to HBV, HCV, and HIV; syphilis remains within the serological screening domain.

NAT should not be considered a universal reference standard for serological screening. ChLIA-positive/NAT-negative results may indicate nonspecific assay reactivity, resolved or treated infection with persistent antibodies, or low-level or intermittent viremia. Conversely, ChLIA-negative/NAT-positive findings may reflect early infection, including window-period or occult hepatitis B virus (HBV) infection. Accordingly, discordant results require interpretation based on the biological markers detected and established donor-screening algorithms.

Ahmad and Rini evaluated 6,335 blood donor samples in Surabaya, of which 6,320 tested negative by both methods, 2 tested positive by both methods, and 13 yielded discordant results, corresponding to an overall agreement of 99.79% (6,322/6,335). Among the discordant samples, eight were serology-positive/NAT-negative with low reactivity indices and subsequently tested negative on confirmatory NAT. The remaining five were serology-negative/NAT-positive, of which three were confirmed positive for HBV, one for human immunodeficiency virus (HIV), and one was negative on pathogen-specific NAT. Despite the high overall concordance, four confirmed NAT-positive donations were identified among initially seronegative samples, highlighting the potential clinical significance of complementary screening. However, these findings are specific to the evaluated assays, testing algorithms, and donor population and cannot be extrapolated to national ChLIA–NAT performance.[14] **Table 3** summarizes the interpretation of concordant and discordant ChLIA–NAT results for HBV, hepatitis C virus (HCV), and HIV.

Window period, residual risk, and occult hepatitis B infection

Residual transfusion risk refers to the probability that an infectious blood donation remains undetected during routine screening. According to World Health Organization (WHO) guidance, major contributing factors include assay failure and the viremic window period. This risk is influenced by assay sensitivity and donor epidemiology, particularly infection incidence among first-time and repeat donors. Therefore, high analytical sensitivity demonstrated under validation conditions does not guarantee the elimination of residual risk in routine blood screening.[10]

Hepatitis B virus (HBV) screening requires differentiation between window-

period infection and occult HBV infection (OBI). Window-period infection occurs when HBV DNA becomes detectable before hepatitis B surface antigen (HBsAg). In contrast, OBI is characterized by the presence of HBV DNA, typically at low or intermittent levels, despite negative HBsAg results. Antibodies against hepatitis B core antigen (anti-HBc) are frequently, but not invariably, detected in OBI. Each screening marker provides distinct information: HBsAg indicates circulating surface antigen, anti-HBc reflects previous or ongoing exposure, and HBV NAT identifies viral DNA within the assay's detection limits. Their diagnostic contributions are therefore complementary rather than interchangeable.[15]

Despite NAT implementation, residual HBV transmission risk persists because low or fluctuating viral loads may remain undetected, particularly with pooled testing. Furthermore, isolated anti-HBc reactivity or persistent antibody responses may warrant donor evaluation even when NAT results are negative, depending on applicable screening policies. Effective HBV screening therefore requires validated complementary assays, donor history assessment, confirmatory testing, quality assurance, and standardized donor and blood component management protocols adapted to local epidemiology and regulatory requirements.

Table 2. Selected studies of chemiluminescence screening performance in blood donors

Study	Platform/ markers	Population and study reference	Source-reported performance	Interpretation limits
Shahin et al., 2025	CLIA and individual-donation NAT for HBV, HCV, and HIV	87,620 Egyptian donations; NAT designated as comparator by the investigators	Sensitivity/ specificity: HBV 94.85%/99.90%; HCV 98.27%/99.80%; HIV 100%/~100%	Source-reported, NAT-defined 2×2 classifications; NAT is not a universal biological gold standard.
Hartaty et al., 2023	ChLIA platform evaluation for HBsAg, anti-HCV, and syphilis	1,184 Indonesian samples; platform evaluation	Sensitivity: 100% for all three markers; specificity: HBsAg 100%, anti-HCV 99.8%, syphilis 100%	Poster abstract; platform-specific supportive evidence.
Tiwari et al., 2020	Serological screening with individual-donation NAT	10,164 Indian donors; individual-donation NAT comparator	Sensitivity 100%; specificity 99.62–99.97%	Marker- and comparator-specific; discordant reactivity requires resolution.
Arcot et al., 2022	ChLIA platform comparison for HBV, HCV, HIV, and syphilis	4,843 Indian donors; platform comparison	Sensitivity: HBV 94.9%, other markers 100%; specificity 99.8–99.9%	Platform-specific findings; HBV false-negative results remained possible.
Kopacz et al., 2024	Alinity s/i donor-screening assays	Pre-implementation validation plus approximately 150,000 routine Polish donations	Sensitivity 100%; specificity 99.92–100%	Pre-implementation and routine phases used different evidence structures; not a class-wide estimate.

Performance values should be interpreted according to assay, marker, study design, donor population, and comparator.

Predictive values, false-reactive results, donor deferral, and blood wastage

Analytical specificity represents the proportion of noninfected specimens correctly identified according to the study-defined reference standard. In contrast, positive predictive value (PPV) reflects the probability that a reactive result corresponds to the comparator-defined condition. Even highly specific assays may yield lower PPVs in low-prevalence donor populations. Therefore, predictive values depend on population characteristics and reference standards rather than solely on the intrinsic performance of chemiluminescence immunoassay (ChLIA).[16]

Indonesian regulations distinguish mandatory blood safety requirements from institution-specific procedures. Minister of Health Regulation No. 91 of 2015 prohibits the transfusion of screening-reactive blood. It establishes provisions for confidential donor notification, counselling, diagnostic referral, and donor eligibility assessment based on confirmatory findings. Donors with confirmed infections are permanently deferred, whereas those with negative diagnostic follow-up may be considered for re-entry under applicable procedures. Minister of Health Regulation No. 11 of 2025 requires blood establishments (Unit Pengelola Darah, UPD) to implement procedures for managing reactive blood components and performing quality control before distribution. Furthermore, BPOM Regulation No. 11 of 2025 establishes requirements for traceability, complaint investigation, quality review, and product recall.[2–4]

These regulatory provisions do not establish a uniform recipient lookback protocol. When recipient tracing or lookback is indicated, the criteria, scope, timing, and documentation must follow applicable national or institutional procedures. Supplemental testing, follow-up intervals, diagnostic referral, donor re-entry, and counselling should be tailored to specific infectious markers and regulatory requirements. Importantly, a reactive screening result warrants further evaluation but does not independently establish a definitive clinical diagnosis.

Table 3. Interpretation of ChLIA-NAT concordance and discordance for HBV, HCV, and HIV

Pattern	Possible interpretation	Blood-safety implication	Policy-linked response
ChLIA + / NAT +	Concordant reactivity; serological marker and viral nucleic acid detected	Component must not be released	Apply the validated reactive-result algorithm, diagnostic referral/counselling, and component disposition required by policy.
ChLIA + / NAT –	Analytical false reactivity, persistent antibody, resolved infection, or low/intermittent viraemia	Potential donor loss and component wastage if poorly resolved	Use marker-specific supplemental testing, donor history, follow-up, and re-entry procedure.
ChLIA – / NAT +	Early/window-period infection; selected occult HBV infection; or unresolved NAT reactivity	Potential residual-risk reduction when infection is confirmed	Quarantine the component, resolve NAT reactivity, investigate the donor, and undertake lookback only when indicated by an applicable validated procedure.
ChLIA – / NAT –	Concordant non-reactivity	Residual risk is reduced but not zero	Maintain quality systems, surveillance, traceability, hemovigilance, and periodic risk reassessment.

Syphilis is not included in the NAT comparison.

Transfusion-medicine perspective: from test result to blood-safety decision

The clinical value of transfusion-transmitted infection (TTI) screening extends beyond analytical results to their integration into blood safety management. Screening outcomes must inform blood component disposition, donor eligibility, counselling, confirmatory testing or referral, traceability, complaint investigation, product recall when indicated, and hemovigilance. Recipient lookback investigations should follow validated procedures rather than rely solely on screening results. Integrating these processes ensures that laboratory testing contributes to comprehensive transfusion risk management.[2–4,17]

Blood donor screening should be distinguished from clinical diagnosis. A reactive screening result requires appropriate blood component management and donor follow-up but does not independently confirm infection. Donor management should incorporate confidential communication, confirmatory assessment or referral, and measures to prevent stigmatization. Similarly, a non-reactive result does not eliminate the possibility of transfusion-transmissible infection.[6]

Evidence from Indonesia provides further insight into recipient safety. Chozie et al. investigated transfusion-associated hepatitis C among children with bleeding disorders before and after the implementation of nucleic acid testing (NAT). Although this single-centre observational study supports the potential relevance of molecular screening to transfusion safety, its before-and-after design limits causal inference and the generalizability of findings to the national level.[18]

Quality systems and implementation requirements

Neither ChLIA nor NAT alone constitutes an adequate blood-safety strategy. Assay selection and verification, internal quality control, external quality assessment, staff competency, traceability, reactive-donor management, component quarantine and disposition, complaint investigation, recall readiness, continuity planning, and hemovigilance determine whether analytical performance translates into safer transfusion.[2–4,11]

For Indonesian UPDs, implementation should begin with regulatory conformity and the assay's donor-screening intended use. Local verification should use predefined acceptance criteria, and procedures should connect reactive results to component control, donor management, traceability, and recall readiness. NAT adoption, configuration, and prioritization should be considered only after assessing pathogen-specific residual risk, infrastructure, confirmatory capacity, quality assurance, supply continuity, and sustainable financing.[2–4] Table 4 summarizes the essential requirements for integrating ChLIA and NAT into TTI screening systems.

Indonesian context and policy implications

Indonesia combines geographic diversity, heterogeneous blood-service capacity, and an important HBV burden. Current regulations provide implementation frameworks for UPD services and quality systems, but this narrative review does not establish comparative cost-effectiveness or a universal national ChLIA-plus-NAT strategy. Policy choices should be supported by local epidemiology, residual-risk estimates, implementation studies, budget-impact or health-economic analysis, and system readiness.[2–4]

For HBV, HCV, and HIV, NAT may add a molecular detection layer for selected window-period and occult infections. Still, the magnitude and value of that layer depend on the pathogen, assay configuration, donor incidence, regulation, and resources. The Indonesian discordance data identify four confirmed NAT yields among 6,335 donations, but one context-specific study cannot support automatic nationwide extrapolation.[14]

Blood safety should remain integrated with donor selection, high-quality serology, risk-appropriate molecular

testing, donor management, traceability, and hemovigilance. Claims about total cost of ownership, cost-effectiveness, or the preferred scale of NAT adoption require formal economic and implementation evidence beyond the scope of this review.

The novelty of this review does not lie in proposing ChLIA or NAT as new technologies, nor in claiming the first comparison between them. Its contribution is conceptual, contextual, and translational: it links sensitivity, specificity, and predictive values to missed infection, window period, residual risk, OBI, false-reactive donor deferral, blood wastage, donor re-entry, counselling, lookback, traceability, and hemovigilance.

The review also frames ChLIA and NAT as complementary safety layers rather than absolute competitors and integrates international evidence with the contemporary Indonesian UPD regulatory framework. This produces a decision-oriented synthesis for assay selection, local verification, IQC/EQA, reactive-donor algorithms, continuity planning, traceability, and total cost of ownership.

Table 4. Essential implementation requirements for ChLIA/NAT within a TTI-screening system

Domain	Essential requirement	Practical indicators
Regulation and intended use	Assay must be authorized and labelled for donor screening; Indonesian UPD standards include ChLIA for HIV, hepatitis B, hepatitis C, and syphilis.	Regulatory documentation, IFU, donor-screening intended use, performance claims.
Local verification	Predefined acceptance criteria before go-live.	Positive/negative panels, precision, lot-to-lot assessment, carryover where relevant.
IQC/EQA	Routine internal control and external quality assessment.	QC trends, EQA/PME performance, CAPA.
Personnel	Documented competency and authorization.	Training, competency assessment, retraining.
Reactive-result algorithm	Repeat testing, quarantine, confirmation/referral, counselling.	Resolution TAT, false-reactive rate, donor follow-up.
Continuity	Maintenance, backup, supply chain.	Uptime, downtime, stock-outs, contingency plan.
Data and traceability	Donor-sample-result-component linkage.	Audit trail, LIS/middleware, lookback readiness.
Economics	Sustainable total cost of ownership.	Cost/test, wastage, QC cost, service contract, NAT yield/value.

Technology should be implemented as part of a quality system rather than as an isolated analyzer acquisition.

Strengths and limitations

A strength of this review is its integration of donor-specific platform evidence, NAT and occult-HBV literature, Indonesian data, regulation, and transfusion-medicine consequences. Its principal limitations are the narrative, single-reviewer directed search; absence of protocol registration, duplicate screening, formal risk-of-bias assessment, and meta-analysis; heterogeneity in assays, markers, comparators, populations, and study designs; and reliance on some abstract-level or context-specific evidence. One Indonesian platform evaluation was available only as a poster abstract and was therefore treated as supportive rather than a primary basis for recommendations. Accordingly, this synthesis supports qualified interpretation rather than pooled class-wide performance or universal policy recommendations.

CONCLUSION

Available evidence indicates high but assay-, marker-, population-, comparator-, and intended-use-dependent ChLIA performance. ChLIA and NAT detect different biological targets and are not interchangeable. NAT can add a molecular safety layer for selected window-period and occult infections but is not a universal biological comparator for every serological condition. Their combined use should therefore be determined by pathogen-specific residual risk, donor epidemiology, regulation, local verification, quality-system capacity, and sustainable resources. Success should be judged across the complete transfusion pathway, including component control, donor management, traceability, and hemovigilance, rather than by sensitivity and specificity alone.

DISCLOSURES

ETHICAL CONSIDERATION

Not applicable.

FUNDING

No specific grant from any public, commercial, or not-for-profit funding agency supported this work.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

A.K. was responsible for conceptualization, methodology, literature search, evidence interpretation, drafting, critical revision, final approval, and accountability for the work.

GENERATIVE AI DISCLOSURE

ChatGPT (OpenAI) assisted with drafting, restructuring, and language editing. The author independently verified the scientific content, calculations, source accuracy, citations, and final wording; no AI system is listed as an author, and the author accepts full responsibility for the submitted work. No original study data or results were generated using AI.

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