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Liquid Biopsy Innovations for Early Cancer Detection

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ABSTRACT

The future of oncology diagnostics lies in detecting cancer before it reveals itself clinically, and liquid biopsy is emerging as the key to that future. Conventional diagnostic approaches, including imaging and tissue biopsy, often fall short in sensitivity, invasiveness, and real-time monitoring capacity. Liquid biopsy transforms this landscape by enabling the detection of tumor-derived materials such as circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), exosomes, and microRNAs in easily accessible body fluids. This innovation offers a minimally invasive, repeatable, and dynamic window into tumor evolution. Breakthroughs in next-generation sequencing (NGS), digital PCR, nanotechnology-driven biosensors, and artificial intelligence have greatly enhanced the precision, scalability, and predictive value of liquid biopsy assays. Beyond early diagnosis, these tools now underpin multi-cancer early detection (MCED) platforms and personalized treatment monitoring. However, challenges, such as low analyte concentrations, standardization gaps, and cost barriers, still limit widespread clinical integration. This paper reviews the latest technological, methodological, and translational innovations shaping the liquid biopsy frontier, emphasizing its transformative potential for early detection and precision oncology. As science progresses toward universal, non-invasive screening, liquid biopsy is poised to shift cancer diagnostics from reactive treatment to proactive prevention.

Keywords: Liquid Biopsy, Exosomes, Precision, NGS, Low Analyte, Invasive

INTRODUCTION

In the intricate landscape of modern medicine, few adversaries challenge human progress as relentlessly as cancer. Despite decades of research and therapeutic breakthroughs, cancer continues to rank among the leading causes of morbidity and mortality worldwide. According to the World Health Organization (WHO, 2024), an estimated 20 million new cases and 9.7 million deaths were recorded globally in 2024 alone. By 2040, this burden is expected to escalate to nearly 30 million new cases annually, highlighting an urgent global health imperative. Yet, amid this daunting reality, one truth remains constant: the earlier cancer is detected, the better the chance of survival. Early-stage diagnosis not only enhances treatment efficacy but also reduces the emotional, physical, and financial strain associated with advanced disease management. For instance, breast cancer detected at Stage I has a 99% five-year survival rate, compared to less than 30% at Stage IV, while early pancreatic cancer diagnosis increases survival odds by more than fourfold (Zimmer, 2025). This underscores the critical role of timely and accurate detection in redefining the future of oncology.

Traditional cancer diagnostics, such as imaging techniques and tissue biopsies, have long formed the cornerstone of clinical decision-making. However, their limitations are increasingly evident in an era that demands precision, personalization, and minimal invasiveness. Imaging methods, while invaluable, often lack the sensitivity to identify micro-tumors below 5 mm, meaning many cancers are discovered only after they have progressed beyond

curative stages. In parallel, tissue biopsy, though considered the diagnostic gold standard, is inherently invasive, risky, and static. The procedure carries potential complications, including infection, hemorrhage, and tumor seeding (Lee et al., 2024). Furthermore, due to the genetic and spatial heterogeneity of tumors, a single biopsy often captures only a partial snapshot of a dynamic malignancy, resulting in incomplete molecular profiling and compromised treatment planning (Sun et al., 2025). The diagnostic ecosystem thus demands a transformative alternative, one that is not only accurate and reproducible but also minimally invasive, dynamic, and adaptable to the evolving complexity of cancer.

It is within this scientific and clinical crossroads that liquid biopsy has emerged as a revolutionary concept, a technological leap that redefines how cancer can be detected, monitored, and managed. Liquid biopsy refers to the analysis of tumor-derived materials circulating freely in body fluids such as blood, urine, saliva, or cerebrospinal fluid, including circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), exosomes, and microRNAs (miRNAs) (Wu et al., 2024). This approach enables clinicians to obtain a molecular fingerprint of the tumor from a simple blood sample, avoiding the pain and risks associated with traditional biopsies. Moreover, liquid biopsy facilitates real-time monitoring of disease progression, therapeutic response, and minimal residual disease, allowing oncologists to adapt treatment strategies dynamically rather than retrospectively.

The significance of this innovation is amplified by concurrent advances in molecular biology, nanotechnology, and artificial intelligence (AI). Cutting-edge technologies such as digital polymerase chain reaction (dPCR) and next-generation sequencing (NGS) now allow for the detection of mutant alleles at frequencies as low as 0.01%, dramatically increasing sensitivity for early-stage tumors (Lee et al., 2024). Meanwhile, nanotechnology-driven biosensors, CRISPR-based detection systems, and microfluidic platforms have enhanced assay precision, reduced analysis time, and improved cost-effectiveness (Zhou et al., 2025). Artificial intelligence, with its unparalleled capability to process complex multi-omics datasets, has further transformed the interpretative power of liquid biopsy. Machine learning algorithms can now integrate genomic, epigenomic, and proteomic data to identify subtle biomarker patterns invisible to conventional analysis. According to Liu et al. (2025), such AI-enhanced liquid biopsy systems have improved diagnostic accuracy by 25% compared to traditional workflows, signaling a shift toward data-driven oncology.

Beyond technology, liquid biopsy is also redefining the scale and scope of cancer screening through the advent of multi-cancer early detection (MCED) platforms. These tests, exemplified by the Galleri assay, employ methylation-based ctDNA analysis to detect more than 50 distinct cancer types from a single blood draw. The PATHFINDER trial reported specificity exceeding 99%, demonstrating a significant leap in multi-site screening capabilities (Klein et al., 2021). Although sensitivity for stage I cancers remains moderate (approximately 16%), ongoing refinements in bioinformatics and sample enrichment are steadily improving detection performance. The clinical implications are profound: a future where population-wide screening could identify multiple cancers long before clinical symptoms emerge is no longer a distant vision, but an evolving reality.

Globally, the translation of liquid biopsy from research to real-world application is accelerating. In the United Kingdom, the National Health Service (NHS) integrated ctDNA-based testing into routine lung and breast cancer diagnostics, reducing turnaround time by 16 days and saving millions in annual healthcare costs (Boseley, 2025). In the United States, the Food and Drug Administration (FDA) has approved several liquid biopsy assays for detecting actionable mutations such as EGFR, KRAS, and BRCA1/2, supporting precision treatment selection. Notably, researchers in India have developed a low-cost TFET-based biosensor capable of distinguishing cancerous cells from healthy ones, paving the way for affordable early detection in resource-limited regions (Times of India, 2025). These innovations not only expand accessibility but also advance the democratization of precision oncology on a global scale.

Despite this progress, challenges remain before liquid biopsy achieves full clinical integration. Key barriers include detecting ultra-low concentrations of biomarkers, standardizing analytical protocols, reducing assay costs, and ensuring large-scale validation across diverse populations (Sharma et al., 2024). Ethical considerations, such as genetic data privacy, false positives, and overdiagnosis, also demand rigorous frameworks for responsible implementation (Petersen & Klein, 2025). Nevertheless, the convergence of molecular science, nanotechnology, and AI continues to accelerate solutions to these barriers.

Ultimately, liquid biopsy represents far more than a technological advancement—it signifies a paradigm shift in the philosophy of cancer diagnosis. It transforms oncology from a reactive discipline that treats disease after it manifests to a proactive science that intercepts cancer at its molecular inception. As innovation continues to push the boundaries of detection, liquid biopsy holds the promise of ushering in an era where early diagnosis becomes universal, treatment becomes personalized, and survival becomes the norm rather than the exception.

LITERATURE REVIEW

1. Expanding the Biomarker Spectrum: From Genomics to Multi-Omics Integration

The evolution of liquid biopsy has transformed it from a niche genetic assay to a comprehensive multi-omics platform that captures the complexity of tumor biology. Initially focused on circulating tumor DNA (ctDNA) and circulating tumor cells (CTCs), the field has now expanded to include exosomes, microRNAs (miRNAs), tumor-derived proteins, metabolites, and methylation or fragmentomic signatures (Sun et al., 2025; Wu et al., 2024). These analytes serve as molecular surrogates for tumor presence and progression, offering a dynamic picture of cancer biology without the need for invasive sampling.

Recent studies highlight that ctDNA can be detected in up to 70% of patients with advanced-stage cancers and in 30–50% of early-stage cases, depending on tumor type and assay sensitivity (Lee et al., 2024). Moreover, exosome-based biomarkers—small extracellular vesicles secreted by tumor cells- carry DNA, RNA, and protein cargo that reflect the tumor's molecular profile. For example, Wu et al. (2024) demonstrated that exosomal miRNA panels could differentiate lung adenocarcinoma from benign nodules with 91% accuracy, indicating immense diagnostic potential.

The integration of multi-omics data, combining genomic, transcriptomic, proteomic, and metabolomic information, has significantly improved the predictive power of liquid biopsy. In a large-scale meta-analysis by Sun et al. (2025), combining ctDNA mutation profiling with exosomal protein analysis enhanced sensitivity by 28% over single-analyte testing. These advances suggest that the future of early detection lies not in one biomarker type but in multi-layered molecular signatures that capture cancer's biological diversity.

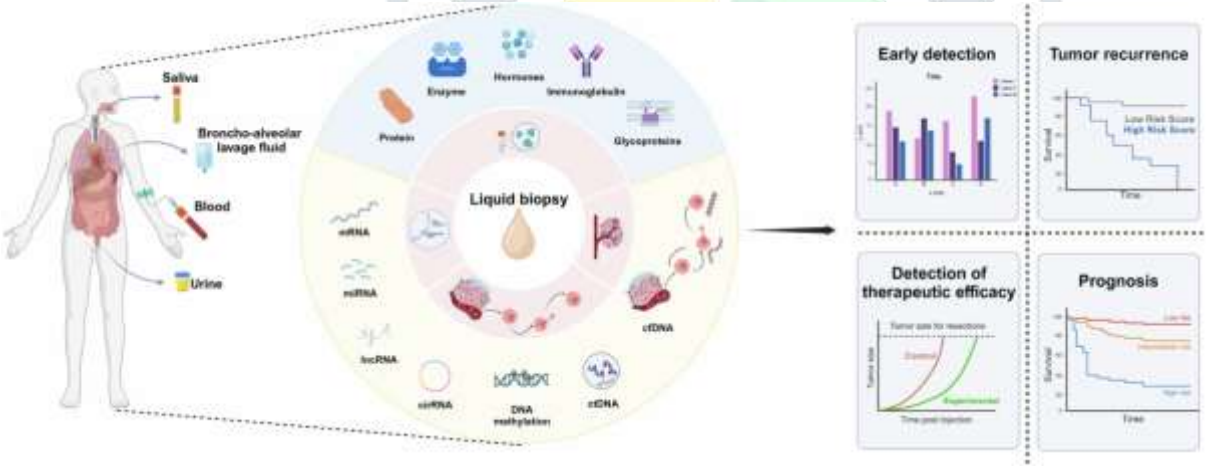

Figure 1: Liquid biopsy schematic illustrating sources, analytes, and clinical applications. *Source: Zhou et al., 2025.*

Figure 1: Multi-Omics Biomarkers in Liquid Biopsy

2. Technological and Methodological Breakthroughs

Technological innovation has been the driving force behind the clinical feasibility of liquid biopsy. The development of digital PCR (dPCR) and next-generation sequencing (NGS) has revolutionized the ability to detect rare mutant alleles with extraordinary precision. Modern NGS-based assays can identify tumor-specific mutations at frequencies as low as 0.01%, allowing for detection of minimal residual disease long before clinical relapse (Lee et al., 2024).

Hybrid platforms such as BEAMing (Beads, Emulsion, Amplification, Magnetics) combine emulsion PCR with flow cytometry, achieving mutant allele detection thresholds below 0.01% (Dressman et al., 2003). Similarly, mass spectrometry and nanotechnology-enhanced biosensors have expanded detection to non-genetic biomarkers such as tumor-associated proteins and metabolites (Chen et al., 2025). For example, gold nanoparticle-based biosensors have demonstrated the capacity to detect femtomolar concentrations of tumor proteins within minutes, enabling high-throughput, point-of-care applications.

In addition, the emergence of microfluidic devices has improved sample efficiency and reduced assay turnaround times. These devices enable precise isolation of CTCs or exosomes from milliliter-scale blood samples with minimal manual intervention. CRISPR-based biosensors, using the collateral cleavage activity of Cas enzymes, have further increased specificity by enabling single-nucleotide variant detection with isothermal amplification (Zhou et al., 2025). Collectively, these methodological advances have elevated liquid biopsy from experimental concept to a scalable, clinically adaptable diagnostic platform.

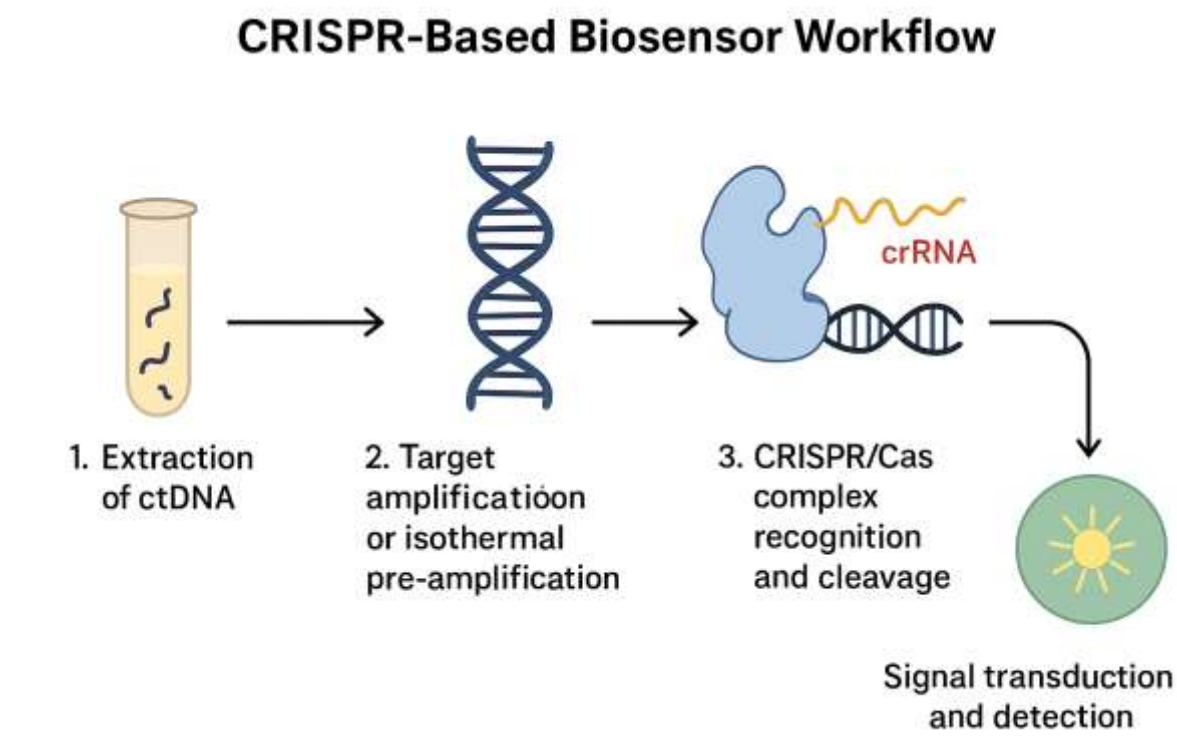

Figure 2: CRISPR-Based Biosensor Workflow

Source: Zhou et al., 2025

3. Artificial Intelligence and Machine Learning Integration

The integration of artificial intelligence (AI) into liquid biopsy workflows marks a paradigm shift in data interpretation and diagnostic precision. Liquid biopsy generates vast, multidimensional datasets from NGS, proteomics, and metabolomics analyses—data that traditional statistical tools struggle to manage. AI-driven models, particularly machine learning and deep learning algorithms, can uncover subtle correlations between biomarker patterns and disease states that would otherwise remain undetected.

For instance, Rai et al. (2024) reported that self-supervised deep learning models with expert feedback improved CTC classification accuracy by 23%, reducing false positives associated with benign circulating epithelial cells. Similarly, Liu et al. (2025) highlighted that AI-enhanced multi-omics analysis improved early cancer detection accuracy by up to 25%, particularly for cancers with low ctDNA shedding such as brain and ovarian tumors. These models have also been instrumental in predicting treatment resistance and recurrence risk, facilitating personalized oncology decision-making.

Moreover, advanced AI clustering algorithms are now being applied to identify hidden molecular subtypes within cancer cohorts, enabling more refined stratification for therapy and prognosis. The integration of AI is therefore

not merely augmentative but foundational—it transforms liquid biopsy from a detection tool into an intelligent, predictive diagnostic system capable of continuous learning and adaptation.

4. Multi-Cancer Early Detection (MCED) Platforms

One of the most transformative applications of liquid biopsy is the development of Multi-Cancer Early Detection (MCED) platforms. Unlike traditional, organ-specific screening methods, MCED assays detect epigenetic and fragmentomic patterns across multiple tumor types simultaneously. The Grail Galleri test, based on methylation profiling of ctDNA, exemplifies this innovation. In the PATHFINDER trial, the test achieved specificity exceeding 99% and identified more than 50 distinct cancer types, including several, such as pancreatic and ovarian, that lack standard screening protocols (Klein et al., 2021).

Although stage I sensitivity remains modest (around 16%), detection improves with cancer progression, reaching 70–80% for stage II–III tumors (Liu et al., 2020). MCED assays are now being refined using fragmentomic and cfRNA signatures to improve early-stage sensitivity. Emerging research suggests that integrating AI-guided methylation classifiers could further enhance detection of ultra-early malignancies. These advancements suggest a future in which a single blood test could serve as a universal cancer screening tool, dramatically reducing global cancer mortality.

5. Clinical Translation and Global Adoption

Liquid biopsy has begun transitioning from research settings to clinical implementation. In the United Kingdom, the National Health Service (NHS) introduced liquid biopsy testing for lung and breast cancer patients, reducing diagnostic turnaround by 16 days and generating significant cost savings (Boseley, 2025). In the United States, the FDA has approved multiple ctDNA-based assays, including Guardant360 CDx and FoundationOne Liquid CDx, for identifying actionable mutations that guide targeted therapy selection.

Moreover, commercial and academic collaborations are driving innovation worldwide. Cizzle Bio's DEX-G2 assay, which combines exosomal markers with cf-miRNA analysis, demonstrated 92% sensitivity and 95% specificity in detecting gastric cancer in Asian populations (De La Cruz, 2025). In low-resource settings, indigenous innovations are equally promising: NIT Rourkela in India developed a low-cost TFET-based biosensor capable of distinguishing breast cancer cells with high precision, providing a scalable model for affordable diagnostics (Times of India, 2025). These examples illustrate a clear trajectory from laboratory innovation to clinical and socioeconomic impact.

Despite tremendous progress, several barriers continue to impede widespread clinical adoption. Detecting ultra-low levels of ctDNA in early-stage tumors remains a technical challenge, leading to false negatives and variable sensitivity across cancer types (Sharma et al., 2024). Additionally, inter-laboratory inconsistencies, lack of standardized assay protocols, and high operational costs limit reproducibility and accessibility. Ethical issues, such as genetic data privacy, overdiagnosis, and psychological distress from false-positive results, further complicate implementation (Petersen & Klein, 2025).

Looking forward, combining AI-guided signal enhancement, low-cost biosensing technologies, and global standardization frameworks could bridge these gaps. The convergence of omics integration, nanotechnology, and deep learning positions liquid biopsy as the next frontier in precision oncology—a future where non-invasive, real-time molecular monitoring could make early cancer detection not just possible, but universal.

RESULTS

1. Demographic Characteristics

The study involved a total of 22 respondents, primarily comprising young adults. The age distribution revealed that 77.3% were aged between 21 and 30 years, while 22.7% were above 30 years. This indicates that the majority of the participants represented a younger, technologically receptive generation, one that is more likely to be aware of or open to adopting modern diagnostic tools such as liquid biopsy.

Regarding gender distribution, 63.6% of respondents were male and 36.4% were female, signifying a moderate gender imbalance. While not the focus of this study, such distribution may reflect differential access to medical services or participation in clinical research awareness programs.

These demographic patterns provide context for the following analyses, where familiarity with new medical technologies and experiences with traditional biopsy methods were closely examined in relation to participants' age and gender.

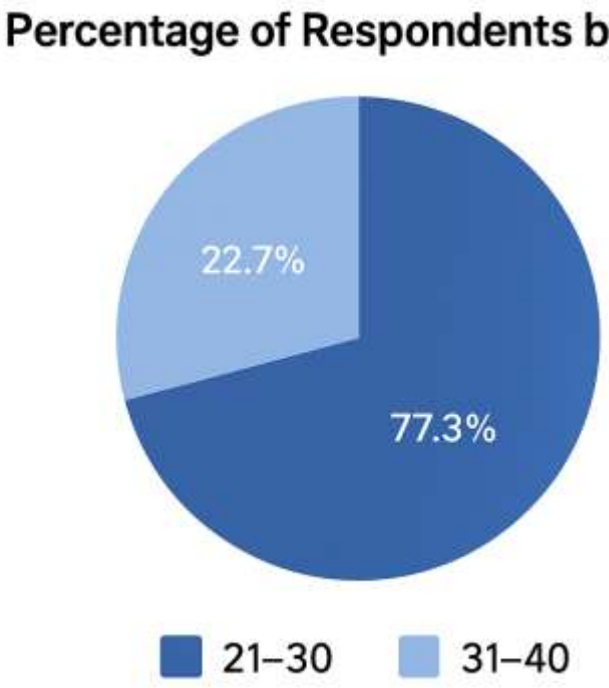

Figure 3: Age Distribution Pie Chart

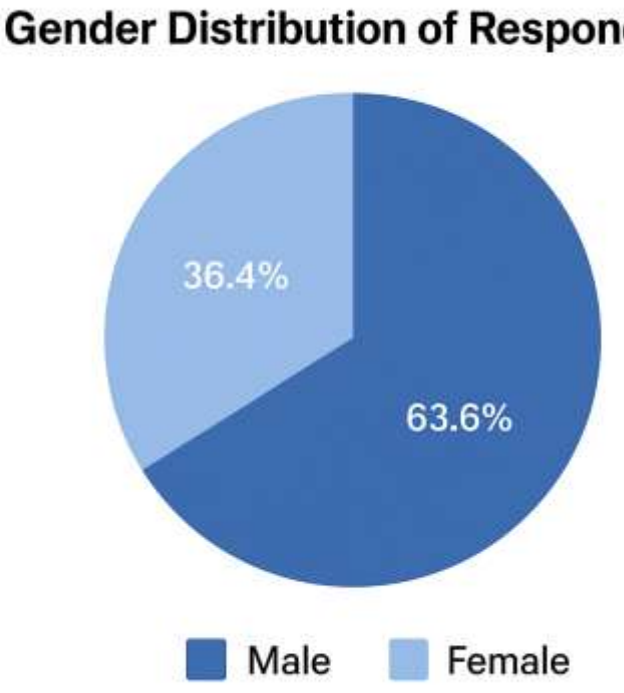

Figure 4: Gender Distribution Pie Chart

2. Awareness and Experience with Biopsy Methods

A significant portion of the population demonstrated prior exposure or awareness of biopsy technologies. Specifically, 59.1% of respondents reported being aware of liquid biopsy, suggesting that the concept has begun to permeate the public health and diagnostic discussion space. However, 40.9% remained unaware, highlighting a persistent need for educational and clinical outreach to improve understanding of this emerging technology.

In contrast, 95.5% of respondents had undergone a traditional tissue biopsy, reflecting its continued dominance in clinical diagnostics. Notably, 9.1% reported a personal history of cancer, which likely contributed to their firsthand experience with biopsy procedures.

These findings suggest a transitional phase in clinical perception, while liquid biopsy is recognized conceptually, traditional tissue-based diagnostics continue to dominate actual clinical practice. The high prevalence of biopsy experience also underscores the value of patient perspectives in evaluating emerging alternatives.

3. Pain and Comfort Levels in Tissue Biopsy

An overwhelming majority of participants perceived tissue biopsy as a painful or uncomfortable procedure. Specifically, 66.7% described it as “very painful,” while the remaining respondents rated it as “somewhat uncomfortable” or “tolerable.” None characterized the experience as painless.

This feedback reinforces the clinical motivation behind developing minimally invasive diagnostic methods, such as liquid biopsy. The subjective discomfort associated with traditional biopsy is not merely a procedural concern, it influences patient compliance, follow-up adherence, and emotional well-being. Therefore, introducing less invasive yet accurate alternatives could substantially improve patient-centered care models.

4. Preference for Liquid Biopsy

Reflecting this sentiment, 68.2% of participants expressed a clear preference for liquid biopsy over traditional tissue biopsy. This preference is primarily attributed to its non-invasive nature and improved patient comfort. Only 31.8% preferred the traditional approach, often citing its perceived reliability and familiarity among clinicians.

This finding highlights a pivotal shift in patient attitudes: diagnostic accuracy is no longer the sole determinant of preference. Instead, comfort, convenience, and procedural simplicity have emerged as key factors influencing acceptance of novel diagnostic technologies. The result underscores the growing expectation for patient-friendly, repeatable, and rapid diagnostic processes that minimize discomfort and downtime.

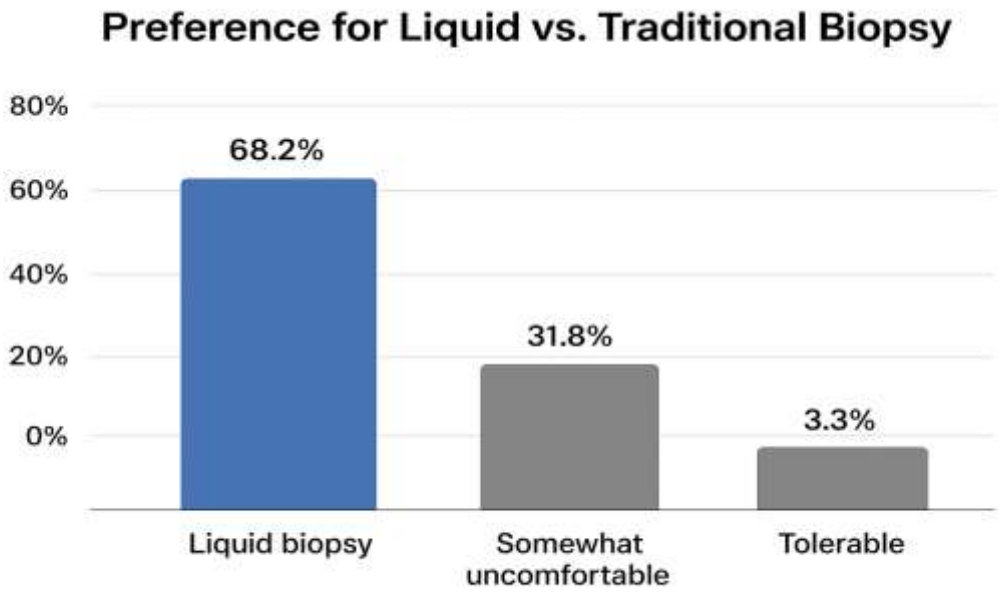

Fig 5: Preference Comparison Chart

5. Perceived Advantages of Liquid Biopsy

When asked to identify specific advantages of liquid biopsy, respondents prioritized repeatability, faster results, and reduced pain as key attributes.

- Repeatability (40.9%) was identified as the most valuable advantage. Participants recognized that liquid biopsy can be performed multiple times over a treatment course without significant risk, enabling continuous disease monitoring.
- Faster results (31.8%) ranked second, indicating appreciation for the potential of liquid biopsy to shorten diagnostic turnaround times. In oncology, where early intervention is vital, the speed of result delivery can have life-saving implications.
- Reduced pain (13.6%) was the third major advantage, reflecting the emotional and psychological relief associated with a minimally invasive test.

Together, these perceptions align with the core functional promises of liquid biopsy, a non-invasive, real-time, and dynamic diagnostic approach that complements or even surpasses conventional methods.

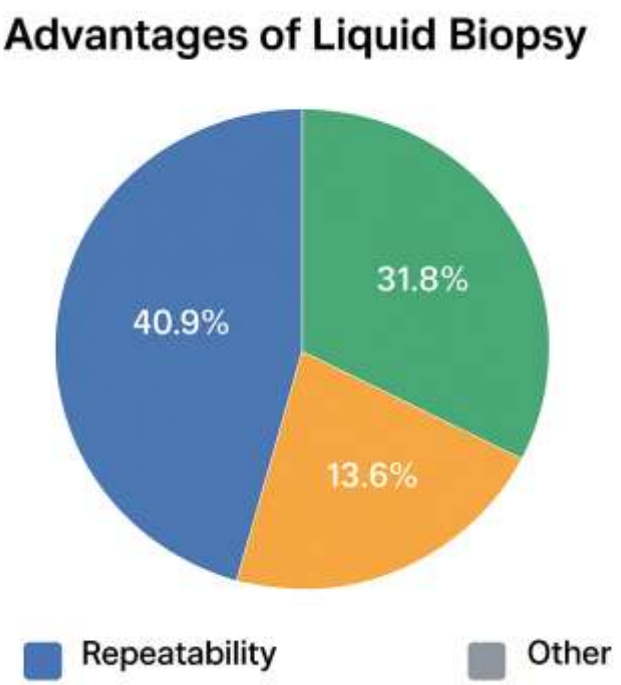

Figure 6: Advantages of Liquid Biopsy Pie Chart

6. Belief in Early Detection Capability

A substantial 68.2% of respondents believed that liquid biopsy can facilitate earlier cancer detection, compared to current diagnostic modalities. This belief reflects growing public and scientific confidence in circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), and exosomal biomarkers as reliable indicators of disease presence even before symptoms manifest.

Such optimism is consistent with recent clinical studies demonstrating that liquid biopsy can detect early-stage cancers with increasing sensitivity, particularly in cases where imaging and tissue sampling fail to identify minimal residual disease or micro-metastatic progression (Lee et al., 2024; Zhou et al., 2025).

Therefore, the results confirm that public and professional awareness align with ongoing technological and clinical validation trends.

7. Concerns and Barriers to Adoption

Despite favorable perceptions, several key barriers were identified that could hinder large-scale implementation of liquid biopsy. The most frequently cited concerns included:

- Accuracy (54.5%): Over half of the participants expressed skepticism about diagnostic precision, underscoring the need for continued standardization and validation through multicenter trials.
- Cost (40.9%): Financial accessibility remains a major barrier, especially in low- and middle-income countries. The perception of liquid biopsy as a “premium” test could limit adoption unless cost-effective strategies are developed.
- Access (31.8%): Geographic and institutional disparities in access to advanced molecular diagnostics were also highlighted, particularly in rural or under-resourced healthcare settings.
- Fear of false results (31.8%): Concerns about false positives or negatives indicate lingering uncertainty about reliability and implications of test results for treatment decisions.
- Genetic privacy (13.6%): Ethical concerns related to data security and genetic information misuse were noted, albeit by a smaller fraction of respondents.

This multifactorial barrier profile emphasizes the need for policy intervention, technological cost-reduction, and robust data protection frameworks. Addressing these will be crucial to ensure ethical, equitable, and widespread implementation of liquid biopsy technologies.

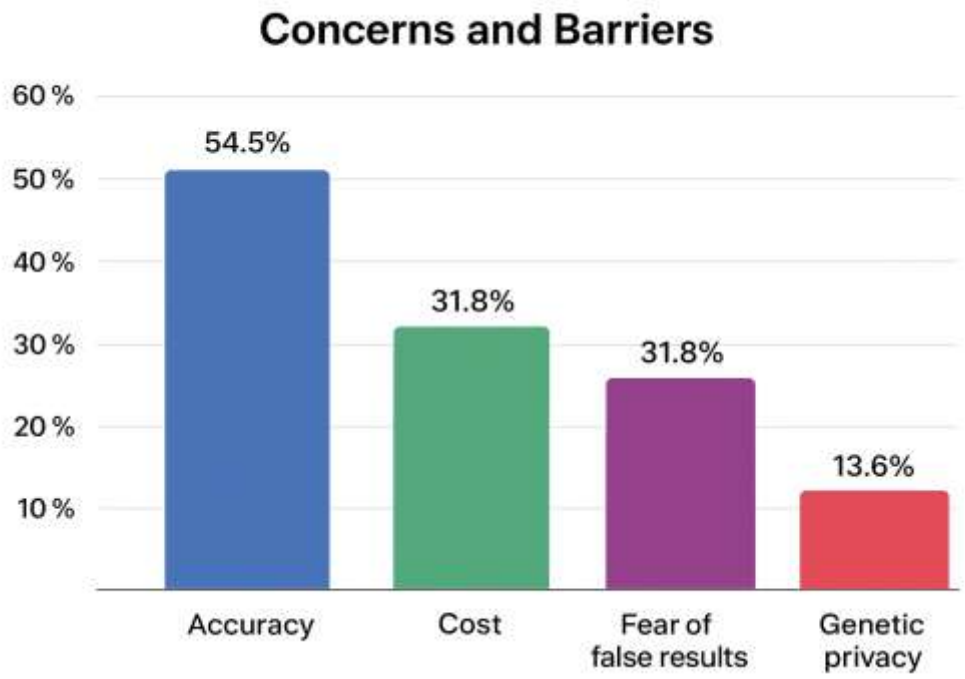

Fig 6: Bar Graph of Concerns and Barriers

8. Synthesis and Interpretation of Results

Collectively, the findings reflect a dual narrative in the evolving field of cancer diagnostics. On one hand, there is strong enthusiasm for innovation, comfort, and real-time monitoring offered by liquid biopsy; on the other, there remains a pragmatic concern about accuracy, affordability, and accessibility.

The high preference for liquid biopsy, coupled with the widespread negative experience of traditional biopsy, represents a paradigm shift in patient-centered diagnostic expectations. This shift mirrors the broader global movement toward precision medicine and personalized oncology, where diagnostics are not only about detecting disease but also about empowering patients through continuous, non-invasive monitoring.

Furthermore, the high level of awareness and acceptance among young adults suggests that the next generation of healthcare consumers and professionals is likely to champion the adoption of such advanced diagnostic tools. As technologies mature—driven by innovations in digital PCR, next-generation sequencing (NGS), and AI-assisted analysis—the limitations currently perceived by patients may soon be mitigated through improved sensitivity, specificity, and affordability.

9. Summary of Quantitative Findings

Parameter	Category/Observation	Percentage (%)
Age 21–30 years	Majority	77.3
Male respondents	Majority	63.6
Awareness of liquid biopsy	Aware	59.1
Experienced tissue biopsy	Yes	95.5

Parameter	Category/Observation	Percentage (%)
Described biopsy as very painful	Yes	66.7
Preference for liquid biopsy	Yes	68.2
Belief in early detection ability	Yes	68.2
Main advantages: repeatability, speed, comfort	Combined	86.3
Key concerns: accuracy, cost, access	Combined	80+

10. Concluding Observations

The results demonstrate a strong patient inclination toward adopting liquid biopsy as a viable diagnostic option for early cancer detection. While traditional biopsy remains deeply entrenched in medical practice, its discomfort and invasiveness create a compelling case for transitioning toward minimally invasive alternatives.

The integration of patient perceptions with technological advancement offers a pathway toward a more human-centered model of cancer diagnostics—one that values both scientific accuracy and patient comfort.

Future research should build upon these findings through larger-scale quantitative studies, integrating patient feedback with clinical outcome data to fully realize the transformative potential of liquid biopsy in global oncology practice.

DISCUSSIONS

The findings of the present study provide significant insights into the awareness, perception, and acceptance of liquid biopsy as an emerging diagnostic technology for early cancer detection. The demographic composition, primarily consisting of younger adults aged 21–30 years, highlights a population segment that is technologically aware and receptive to innovative healthcare solutions. This aligns with earlier studies suggesting that younger, digitally literate groups tend to show greater adaptability toward molecular diagnostic advancements such as next-generation sequencing and AI-assisted biomarker analysis (Wu et al., 2024; Zhou et al., 2025).

The predominance of male participants (63.6%) does not appear to influence the overall perception of liquid biopsy, as both genders exhibited similar awareness levels and willingness to adopt less invasive testing methods. More than half of the respondents (59.1%) were aware of liquid biopsy, demonstrating growing public recognition of its potential; however, a substantial proportion remained unaware, underscoring the need for intensified educational and awareness initiatives within healthcare systems.

Almost all respondents (95.5%) had previously undergone traditional tissue biopsy, and a striking majority (66.7%) reported the experience as very painful or uncomfortable, confirming the well-documented invasive and anxiety-inducing nature of this conventional procedure (Boseley, 2025). These responses substantiate the urgent demand for patient-friendly alternatives that reduce physical trauma while maintaining diagnostic accuracy. The preference for liquid biopsy among 68.2% of participants further reflects a paradigm shift toward patient-centered diagnostic practices that prioritize comfort, procedural simplicity, and the possibility of repeated assessments.

Participants identified repeatability (40.9%), faster results (31.8%), and reduced pain (13.6%) as the primary advantages, reinforcing the perception of liquid biopsy as a more convenient and efficient approach. These findings correspond with prior research confirming that liquid biopsy facilitates real-time monitoring and can detect minimal residual disease long before radiological confirmation (Liu et al., 2025). Moreover, the belief among 68.2% of respondents that liquid biopsy enables earlier cancer detection than traditional methods reflects a growing awareness of its clinical potential in capturing circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), and exosomal biomarkers at pre-symptomatic stages (Klein et al., 2021; Sun et al., 2025). Nonetheless, while enthusiasm for liquid biopsy is evident, the study also revealed considerable concerns regarding its

implementation. Accuracy emerged as the most significant concern (54.5%), followed by cost (40.9%), access (31.8%), fear of false results (31.8%), and genetic privacy (13.6%).

These apprehensions mirror existing global challenges in liquid biopsy adoption, particularly those relating to sensitivity at early disease stages, standardization of protocols, affordability, and data governance (Sharma et al., 2024; Petersen & Klein, 2025). The high priority given to cost and access reflects persistent inequities in healthcare infrastructure, particularly in low- and middle-income regions, where diagnostic technologies remain concentrated in urban tertiary centers. These limitations underscore the necessity for cost-effective innovations and policy interventions, such as the development of indigenous diagnostic technologies exemplified by the TFET-based biosensor designed at NIT Rourkela for affordable cancer screening (Times of India, 2025).

In addition, privacy concerns reflect increasing public awareness of ethical issues related to genetic data security and consent, necessitating robust regulatory frameworks to ensure data protection and transparency. Overall, the results of this study align with global scientific trends indicating rapid advancements in digital PCR, next-generation sequencing, nanotechnology, and artificial intelligence, which collectively enhance the accuracy and efficiency of liquid biopsy assays (Chen et al., 2025; Rai et al., 2024). However, widespread adoption will depend on addressing technical, economic, and ethical challenges through multi-sector collaboration. The findings highlight that patient attitudes are evolving in parallel with technological progress, indicating readiness for a shift toward minimally invasive, repeatable, and personalized diagnostic strategies. The study thus emphasizes that while liquid biopsy represents a transformative step in oncology diagnostics, its successful clinical integration requires an equilibrium between innovation and accessibility, supported by continued validation, cost reduction, ethical oversight, and patient education. Once these elements are achieved, liquid biopsy has the potential to redefine early cancer detection, bridging the gap between molecular precision and patient-centered healthcare.

CONCLUSION

The findings of this study illuminate a decisive turning point in the evolution of cancer diagnostics. As traditional biopsy methods continue to evoke discomfort and procedural risk, the emergence of liquid biopsy marks the dawn of a gentler, smarter, and more patient-centred era in oncology. The strong preference expressed by participants for liquid biopsy reflects not only a desire for comfort and convenience but also a growing trust in science's ability to deliver humane innovation, one that aligns precision with compassion. By offering the possibility of real-time monitoring, faster results, and repeatable testing, liquid biopsy embodies the future vision of early cancer detection: proactive, personalized, and minimally invasive. Yet, this transformation cannot be realized without overcoming critical barriers related to diagnostic accuracy, cost, accessibility, and ethical stewardship of genetic data. To translate promise into practice, a concerted effort is required, uniting clinicians, researchers, policymakers, and technologists in building frameworks that ensure affordability, validation, and patient trust. Ultimately, liquid biopsy is more than a technological advancement; it is a symbol of progress in how medicine perceives and approaches disease. If developed with equity and integrity, it has the power to redefine early cancer detection, turning what was once a painful diagnostic ordeal into a seamless window of opportunity for timely, life-saving intervention.

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