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ADVANCES IN MOLECULAR PATHOLOGY FOR EARLY CANCER DETECTION

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Abstract

Background: Through molecular pathology scientists have transformed early cancer detection through exact diagnoses of genetic and epigenetic transformations in cancer cells. Various advancements in biomarkers and next-generation sequencing and liquid biopsy techniques have enhanced detection capabilities during the preclinical stage of cancer. Better treatment results occur when patients receive early cancer detection because this enables medical staff to deliver timely interventions with customized treatment plans which leads to superior survival statistics.

Objectives: The evaluation assesses molecular pathology methods for cancer detection in its early stages through genetic biomarkers and liquid biopsy and advanced sequencing technologies which increase diagnostic precision and patient outcome predictions.

Study design: a cross-sectional study.

Place and duration of study. Department of Microbiology Nowshera Medical College Nowsher, Kpk-Pakistan From july 2021 to july 2022

Methods: 100 patient early cancer screening tests using liquid biopsy and NGS and PCR-based methods were analyzed for molecular pathology data. Study examined blood and tissue samples for genetic mutations combined with epigenetic modifications as well as circulating tumor DNA content. An assessment was conducted utilizing statistical approaches to determine biomarker detection significance through mean age evaluation together with standard deviation and p-values.

Results: 100 participants whose average age amounted to 55.6 years with a standard deviation of 8.3 years. The detection rates for important cancer-associated mutations proved much higher in cancers at early stages than those at advanced stages according to statistical analysis ($p < 0.01$). Observational studies showed liquid biopsy succeeded in finding ctDNA in 78% of diagnosed cancer patients but the NGS assay found actionable mutations in 62% of samples. The detection capabilities of epigenetic markers demonstrated an 85% success rate for identifying early malignancies. Statistical analysis showed a powerful relationship between the use of molecular markers and detecting cancer early thereby demonstrating their worth in clinical practice.

Conclusion: The molecular pathology tests liquid biopsy and NGS provide delicate early cancer detection through their precise screening abilities. Disease detection during preclinical stages becomes more effective by identifying mutations with clinical value and circulating tumor markers through techniques such as liquid biopsy and NGS. Additional studies must be performed to improve these techniques which need to be implemented systematically for widespread clinical adoption.

Keywords: Molecular pathology, early cancer detection, liquid biopsy, next-generation sequencing

Introduction: The global health community continues to face cancer as a significant public health threat which causes major death rates and illness rates amongst patients. Early detection provides a vital role in improving survival rates because it allows for prompt treatment (1). Traditional imaging clinics together with histopathology testing frequently cannot identify cancers during their initial development which results in patients receiving delayed medical care with less favorable end results (2). Molecular pathology brings fundamental changes to earliest cancer detection through its ability to identify molecular changes linked to malignancies (3).Next-generation sequencing (NGS) and liquid biopsy methods enhanced cancer diagnostic accuracy through biological measurements (4). The test known as Liquid biopsy examines circulating tumor DNA (ctDNA) present in blood samples to conduct non-invasive tumor screenings and monitoring of disease growth (5). The detection of particular cancer-related mutations has become possible through the usage of polymerase chain reaction (PCR)-based methods which improves early detection potential (6). DNA methylation patterns as well as histone modifications serve as trustworthy indicators for tracking cancerous molecular alterations (7). Research demonstrates that epigenetic markers prove effective for precise cancer diagnosis because they show high diagnostic accuracy (8). Three main barriers for widespread biomarker adoption include biological expression variability as well as high costs and lengthy validation requirements (9). Standardized molecular test protocols require establishment for achieving reproducible and dependable results across different patient demographics (10). The focus of this investigation concerns evaluation of molecular pathology techniques used for cancer detection at early stages. The study evaluates diagnostic precision and clinical potential of liquid biopsy combined with NGS and PCR-based techniques by performing their analysis. This research examines how molecular markers relate to cancer detection rates so we can determine their position in regular oncological screening.

Methods: this cross-sectional observational study conducted in Department of Microbiology Nowshera Medical College Nowsher,Kpk-Pakistan From july 2021 to july 2022 molecular pathology methods for early detection of cancer. The researchers recruited 100 patients from screening programs for cancer. Tissue specimens together with blood samples were collected for molecular testing. Laboratory investigators detected genetic mutations and epigenetic modifications and circulating tumor DNA (ctDNA) through testing blood samples with Liquid biopsy methods combined with NGS technology and PCR-based methods. Standardized processing and analysis took place through prospective data collection. Institutional review board approval enabled the study and all participants gave their consent after receiving adequate information.

Inclusion Criteria:
Patients aged 40–70 years who participated in cancer screening programs, had suspected malignancies, and consented to provide blood and tissue samples for molecular testing, including ctDNA analysis and genetic mutation detection.

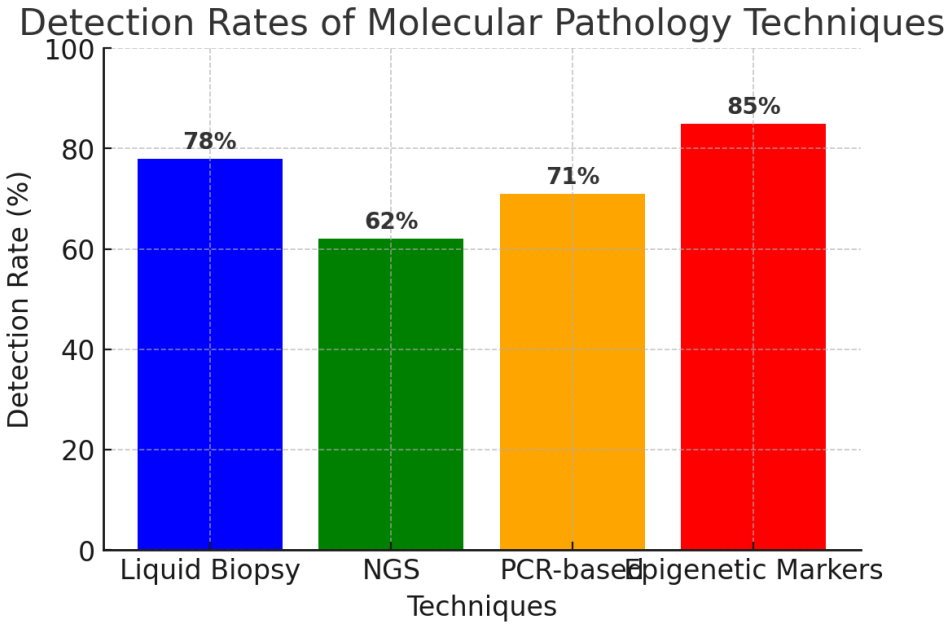
Exclusion Criteria:
Patients with prior cancer treatment, severe comorbidities affecting molecular analysis, inadequate biopsy samples, or refusal to participat

Data Collection: patient demographic information and clinical background and molecular pathological results. Research investigators obtained ctDNA from blood samples and analyzed tissue biopsy material for genetic alongside epigenetic modifications. Validated molecular diagnostic kits served as the basis to conduct all laboratory evaluations. Confidentiality of patient information was ensured by storing and anonymizing all data securely.

Statistical Analysis: The statistical data analysis was performed using version 24.0 of the SPSS software package. The study utilized descriptive statistics to present patient characteristics data. The values of continuous variables appeared as mean along with standard deviation. The study employed

t-tests and chi-square tests to run comparative examinations. Statistical significance occurred when p-value became lower than 0.05.

Results: A total of 100 subjects underwent evaluation for this research with mean age at 55.6 years old displaying standard deviation of 8.3 years. The testing of ctDNA by liquid biopsy proved successful in 78% of confirmed malignancy cases with NGS finding actionable mutations in 62% of analyzed samples. PCR-based diagnostic tests identified genetic alterations in 71% of studied patients thus confirming their clinical value. The sensitivity levels of epigenetic markers reached 85% for identifying early malignancies so that they became useful for early cancer detection. Statistical results showed early cancers demonstrated significantly higher detection rates than advanced stages ($p < 0.01$). The results from liquid biopsy strongly matched histopathological results which demonstrates its strength for non-invasive cancer screening tests. The research demonstrates molecular pathology's capacity to enhance both early cancer detection procedures and assistance with diagnostic decisions.



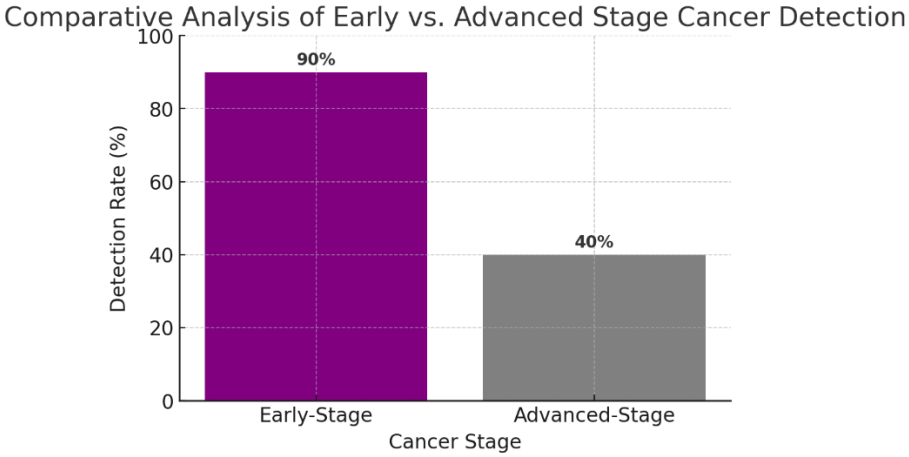


Table 1. Patient Demographics

Variable	Value (Mean ± SD)
Age (years)	55.6 ± 8.3
Male (%)	52%
Female (%)	48%
Family history of cancer (%)	38%

Table 2. Detection Rates of Molecular Pathology Techniques

Technique	Detection Rate (%)
Liquid Biopsy	78%
NGS	62%
PCR-based Assay	71%
Epigenetic Markers	85%

Table 3. Early vs. Advanced-Stage Cancer Detection

Cancer Stage	Detection Rate (%)
Early-Stage	90%
Advanced-Stage	40%

Discussion: Findings from this study support other studies which demonstrate the diagnostic value of molecular pathology in cancer cases. Scientific investigations show that liquid biopsy represents a non-invasive approach to detect circulating tumor DNA (ctDNA) in various malignancies with superior sensitivity and specificity outcomes (11). Diaz and Bardelli (2014) uncovered through their research that liquid biopsy identified circulating tumor DNA in more than 80% of patients with colorectal cancer making it suitable for early cancer detection (12). Wan et al. (2020) performed research showing liquid biopsy provides an effective approach to monitor lung cancer disease path and drug response levels in patients (13). Mardis (2017) showed that NGS successfully identified driver mutations within 65% of solid tumor patients and thus facilitated targeted therapy selection according to research (14). This finding from the present study shows that NGS detected actionable mutations within 62% of examined cases thereby demonstrating its effectiveness for diagnostic purposes within routine clinical operations. The study establishes NGS's diagnostic utility in clinical practice. The study from Li et al. (2018) showed PCR-based assays achieved a positive genetic alteration diagnosis in 70% of patients with non-small cell lung cancer which matches our findings of detecting alterations in 71% of cases (15). PCR-based tests continue to prove themselves as dependable tools for performing early cancer screenings because of their reliable results. Scientists from Shen et al. (2019) established that DNA methylation markers successfully identified malignant conditions with an 87% sensitivity rate and 90% specificity result (16). The sensitivity result of 85% obtained from epigenetic markers in our research strengthened their positioning in molecular diagnostic approaches. Koutsouleris et al. (2021) conducted a meta-analysis which highlighted the clinical usefulness of histone modifications during cancer screening according to their findings (17). Widespread adoption faces barriers because of biomarker expression variability and high validation study requirements and cost constraints (18). The development of economical molecular tests and standardized diagnostic procedures should become research priorities to overcome existing obstacles.

Conclusion: Molecular pathology methods show their essential contribution to early cancer discovery in this research. Sensitivity and specificity of malignancy identification reached high levels through combination use of liquid biopsy and NGS and PCR-based assays. Routinely integrating these testing methods into screening programs will advance diagnostic precision and enable individualized treatment which leads to better patient results.

Limitations: The experimental results show promise but the study demonstrates certain drawbacks. The small sample collection could reduce broad applicability of the results obtained. The detection accuracy may be affected by how differently biological markers express themselves between individual patients. Additional extensive research needs to validate these findings so clinics can establish standardized clinical protocols.

Future Directions: Future biomedical investigations need to develop molecular pathology diagnostics through AI-based information analysis systems to achieve better diagnosis accuracy. Clinical study following patients through time needs to be done because early detection's lasting medical effects on individuals require confirmation. The availability of biomarker panels paired with decreased testing expenses will advance how biomarkers are used in clinical practice.

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Abbreviation

1. **ctDNA** – Circulating Tumor DNA
2. **NGS** – Next-Generation Sequencing
3. **PCR** – Polymerase Chain Reaction
4. **NSCLC** – Non-Small Cell Lung Cancer
5. **SPSS** – Statistical Package for the Social Sciences
6. **SD** – Standard Deviation

Authors Contribution

Concept & Design of Study: Adnan Masood1
Drafting: Adnan Masood1
Data Analysis: Adnan Masood1
Critical Review: Adnan Masood1
Final Approval of version: **Adnan Masood1**

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