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Digital AI-Based Sensing Technologies in Cancer Care: A PATHS Framework for Early Detection and Personalized Diagnosis

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ABSTRACT

Background: Recent work has mapped a wide range of biotechnological tools for early cancer detection, ranging from microfluidics and liquid biopsy to biosensors, organoids, breath-based diagnostics, and artificial intelligence (AI), with explicit attention to primary and resource-constrained healthcare settings. However, global experience with multi-cancer early detection (MCED) tests and liquid biopsy shows that technology alone does not guarantee earlier diagnosis or reduced mortality.

Purpose: This short communication proposes a pragmatic, pathway-first framework to complement tool-centric narratives and to help clinicians, policymakers, and innovators integrate emerging technologies into real-world primary healthcare systems, especially in low and middle-income countries (LMICs).

Methods: A focused narrative synthesis of recent literature from 2022 to 2025 was performed on early cancer detection, MCED, liquid biopsy, biosensors, breath-based diagnostics, radiomics, and AI in oncology, prioritizing peer-reviewed sources indexed in major biomedical databases. Insights from implementation science and equity-oriented cancer control in LMICs were integrated to co-develop a framework aligned with healthcare delivery and organization.

Results: Three key blind spots in purely tool-focused narratives were identified, namely limited integration of implementation science and health system readiness, insufficient attention to affordability, reimbursement, and financing, and lack of use-case clarity across screening, triage, diagnosis, and monitoring. To address these gaps, the PATHS framework is introduced: Performance for purpose, Access and affordability, Trust and ethics, Health system fit, and Sustainability. Its application is illustrated for wearable biosensors, breath-based tests, paper-based microfluidics, liquid biopsy, and radiomics or AI at different levels of care.

Conclusions: Biotechnological innovation for early cancer detection is now rich and diverse. The next step is to embed these tools into implementable, equity-sensitive pathways. Adopting a PATHS lens can help readers move from asking "which tool is most exciting?" to "which tool, in which pathway, for which population, delivers the greatest real-world benefit?", particularly in primary healthcare and LMIC settings where the marginal gains from earlier detection are greatest.

1. Introduction

Early detection is one of the most powerful levers to reduce global cancer mortality. Recent GLOBOCAN 2022 estimates highlight a continuing rise in cancer incidence and deaths across many regions, with the greatest proportional burden in low and middle-income countries (LMICs) (Bray *et al.*, 2024). At the same time, there is strong biological and clinical consensus that shifting diagnosis toward earlier stages is critical for improving survival, reducing treatment complexity, and alleviating the financial and social burden on patients and health systems (Crosby *et al.*, 2022).

Over the past decade, biotechnological innovation in oncology has expanded rapidly. Multicancer early detection (MCED) tests, liquid biopsy, microfluidic platforms, wearable biosensors, organoid models, breath-based

diagnostics, and AI enabled radiomics are increasingly reported as promising tools for detecting cancer at earlier, potentially curable stages (Ajikumar & Lei, 2024; Ge *et al.*, 2024; Valizadeh *et al.*, 2025; Hegade *et al.*, 2025; Wu & Liu, 2025). Recent reviews and health-technology assessments emphasize that technology alone does not guarantee earlier diagnosis or reduced mortality, and that implementation pathways and health-system readiness are decisive for population impact (Milner & Lennerz, 2024; Wade *et al.*, 2025; Xu *et al.*, 2025).

Yet experience with MCED tests, liquid biopsy platforms, and AI enabled imaging underscores a central tension: innovation without implementation can widen inequities (Milner & Lennerz, 2024; Bamodu & Chung, 2024; Wade *et al.*, 2025). High performance tools may remain confined to tertiary centres or elite populations if they do not fit primary care workflows, financing mechanisms, regulatory environments, and community expectations. In LMICs, where pathology and imaging infrastructure are often fragmented and where out of pocket expenditure remains high, the risk that sophisticated technologies primarily benefit already advantaged groups is substantial (Bamodu & Chung, 2024; Bray *et al.*, 2024).

Furthermore, many discussions of early detection group together tools designed for very different points along the cancer continuum, including population screening, high risk triage, diagnostic confirmation, treatment selection, and minimal residual disease (MRD) monitoring, without clearly distinguishing their respective performance thresholds, resource requirements, or policy implications (Crosby *et al.*, 2022; Sahoo *et al.*, 2025). For primary healthcare systems, this lack of use case clarity can make it difficult to prioritise investments and design coherent pathways.

This short communication builds on recent international reviews (Xu *et al.*, 2025) to propose a pathway oriented, pragmatic framework, PATHS, for integrating early cancer detection tools into primary healthcare systems, with particular attention to LMIC realities. By foregrounding implementation science, equity, and health system fit, PATHS aims to help clinicians, policymakers, and innovators decide which tools should be placed where in real world care pathways.

2. Methodology

This work is a conceptual, narrative synthesis rather than an empirical trial. A focused literature scan (2022–2025) was conducted using PubMed, Scopus, Web of Science, and Medline, emphasising four domains: epidemiology and policy perspectives on early cancer detection and stage shift (Bray *et al.*, 2024; Crosby *et al.*, 2022); technology oriented reviews of microfluidics, biosensors, organoids, liquid biopsy, radiomics, and AI (Ajikumar & Lei, 2024; Ge *et al.*, 2024; Hegade *et al.*, 2025; Iqbal *et al.*, 2022; Valizadeh *et al.*, 2025; Huhulea *et al.*, 2025; Sahoo *et al.*, 2025; Wu & Liu, 2025); recent MCED and liquid biopsy implementation analyses (Milner & Lennerz, 2024; Wade *et al.*, 2025; Xu *et al.*, 2025); and equity focused perspectives on cancer control in LMICs (Bamodu & Chung, 2024).

Sources were selected if they (i) directly addressed early detection technologies, (ii) discussed implementation or equity implications, or (iii) provided syntheses relevant to pathway integration in primary care. No systematic review procedures were applied; instead, the goal was to use these studies to co-develop an implementation-oriented framework aligned with healthcare delivery and organization.

3. From Tools to Pathways: Gaps in the Current Narrative

Xu *et al.* (2025) provides a comprehensive and clinically grounded catalogue of tools, highlighting non-invasive sampling, multiplex biomarker detection, and the potential for low-cost platforms such as paper-based microfluidics and wearable biosensors (Ajikumar & Lei, 2024; Iqbal *et al.*, 2022; Wu & Liu, 2025). This is particularly relevant for primary care and district level health facilities, where minimally invasive, easy to use, rapid tests are attractive.

When recent tool centric narrative is juxtaposed with recent MCED and implementation literature (Crosby *et al.*, 2022; Milner & Lennerz, 2024; Wade *et al.*, 2025), three important gaps emerge:

Implementation science and health system readiness are under specified: Liquid biopsy and MCED technologies face practical barriers, including preanalytical variability, laboratory capacity, workforce skills, and regulatory frameworks, that can limit deployment even in high income settings (Ge *et al.*, 2024; Hegade *et al.*, 2025; Wade *et al.*, 2025). Many tools described by Xu *et al.* (2025) will require robust quality systems, data infrastructure, and supply chains that are often weak in LMIC primary care. Without explicit attention to readiness, tools risk being piloted in controlled environments but failing at scale.

- **Equity, affordability, and reimbursement are not central:** Several platforms promise low per test cost, yet real world expenses related to capital equipment, proprietary reagents, informatics, and follow up investigations can be substantial (Iqbal *et al.*, 2022; Hegade *et al.*, 2025). In the absence of context specific health technology assessment (HTA), cost effectiveness analyses, and reimbursement planning, innovation risks reinforcing existing disparities in cancer care (Bamodu & Chung, 2024). For primary healthcare, where

budgets are constrained and trade-offs are unavoidable, neglecting affordability can derail otherwise promising tools.

- **Use case clarity across the cancer continuum is limited:** Tools for population screening, high risk triage, diagnostic confirmation, treatment selection, and MRD monitoring are often grouped together under the umbrella of early detection (Crosby *et al.*, 2022; Ge *et al.*, 2024; Sahoo *et al.*, 2025). Yet each use case carries different thresholds for acceptable sensitivity, specificity, positive predictive value, and downstream resource use (Milner & Lennerz, 2024; Wade *et al.*, 2025). For example, a triage test in primary care may tolerate lower specificity if it is inexpensive and followed by confirmatory imaging, whereas a population wide screening test must be highly specific to avoid overwhelming limited diagnostic capacity.

To move from promise to practice, primary healthcare systems need a structured way to decide which tool fits where, and under what constraints.

4. The PATHS Framework for Early Cancer Detection

The PATHS framework Performance for purpose, Access and affordability, Trust and ethics, Health system fit, and Sustainability is proposed to guide integration of biotechnological tools into early cancer detection pathways.

4.1. Performance for Purpose

Performance should be judged relative to the intended use case, not in isolation. For example, a breath based volatile organic compound (VOC) test with high negative predictive value may be ideal as a low-cost triage tool, whereas circulating tumour DNA (ctDNA) based liquid biopsy may be more suitable for MRD monitoring or treatment selection (Ge *et al.*, 2024; Wang *et al.*, 2022; Kommineni *et al.*, 2025; Milner & Lennerz, 2024).

Recent syntheses report key performance metrics for microfluidics, biosensors, organoids, and AI radiomics tools (Ajikumar & Lei, 2024; Valizadeh *et al.*, 2025; Xu *et al.*, 2025). PATHS encourages readers to ask explicitly:

"Is this tool optimised for population screening, targeted triage, diagnostic confirmation, or longitudinal monitoring, and are the performance thresholds aligned with that role?"

`Clarifying the primary purpose helps prevent misapplication of tools outside their validated context.

4.2. Access and Affordability

True access extends beyond analytic sensitivity to availability, affordability, and last mile logistics. Paper based microfluidics and nano enabled biosensors can often be manufactured cheaply and used at or near the point of care (Ajikumar & Lei, 2024; Iqbal *et al.*, 2022), whereas liquid biopsy platforms may require central laboratories, cold chains, and sophisticated bioinformatics (Ge *et al.*, 2024; Hegade *et al.*, 2025).

In LMIC settings, fragmented financing, weak pathology infrastructure, and limited political commitment already constrain access to basic cancer diagnostics (Bamodu & Chung, 2024). Embedding metrics such as cost per early-stage cancer detected, staff time, and referral capacity into early pilot evaluations would better align these tools with policymakers' decisions and with the journal's focus on healthcare organisation and management (Bray *et al.*, 2024; Bamodu & Chung, 2024).

4.3. Trust and Ethics

Many of the tools highlighted by Xu *et al.* (2025), including AI guided imaging, multi omics signatures, and radiomics models, function as black boxes to both clinicians and patients (Huhulea *et al.*, 2025; Huang *et al.*, 2025; Valizadeh *et al.*, 2025; Sahoo *et al.*, 2025). Breathomics and wearables similarly raise questions about data privacy, continuous monitoring, over diagnosis, and false reassurance (Wang *et al.*, 2022; Wu & Liu, 2025).

A PATHS lens foregrounds trust building measures, including transparent reporting of false positive and false negative rates, culturally sensitive communication of probabilistic results, and clear governance of data storage, sharing, and secondary use.

In settings where cancer is stigmatised and primary care is overstretched, building trust may be as important as improving test accuracy (Bamodu & Chung, 2024).

4.4. Health System Fit

Biotechnological tools should be mapped to specific levels of care and integrated with existing workflows:

- **Community and primary care** wearable devices and simple biosensors for high-risk cohorts; symptom driven breath tests and paper-based microfluidics for initial triage (Ajikumar & Lei, 2024; Wang *et al.*, 2022; Wu & Liu, 2025).
- **District hospitals and laboratories** more complex microfluidic platforms, immunoassays, and basic molecular tests that can operate within existing laboratory infrastructure (Ajikumar & Lei, 2024; Iqbal *et al.*, 2022; Hegade *et al.*, 2025).

- **Tertiary centres** liquid biopsy assays, organoid platforms, and radiomics or AI pipelines supporting risk refinement, treatment planning, and MRD surveillance (Ge *et al.*, 2024; Ma *et al.*, 2023; Valizadeh *et al.*, 2025; Sahoo *et al.*, 2025).

For the journal's readership, this mapping is crucial, as it translates promising bench level tools into concrete decisions on task shifting, referral thresholds, training needs, and capital investment.

4.5. Sustainability and Learning

Sustainability requires that early detection programmes function as learning health systems rather than one off projects. MCED evaluations increasingly use longitudinal cohorts and registry linkages to refine thresholds and quantify over diagnosis and stage shift (Milner & Lennerz, 2024; Wade *et al.*, 2025).

Embedding minimal common data elements, including test type, cancer stage at diagnosis, sociodemographic variables, referral patterns, and outcomes, into pilots of breathomics, microfluidics, biosensors, and wearables would allow countries to iteratively adapt pathways to local realities (Xu *et al.*, 2025; Ajikumar & Lei, 2024; Wang *et al.*, 2022; Wu & Liu, 2025). Iterative learning can then be used to update guidelines, refine risk thresholds, and discontinue tools that do not add sufficient value.

5. Illustrative Use Cases in Primary Healthcare

5.1. Wearable Biosensors as Risk Escalation Triggers

Recent reviews position wearable biosensors as promising tools for continuous monitoring of physiological and biochemical markers relevant to cancer and its risk factors (Kashaninejad *et al.*, 2025; Wu & Liu, 2025). Rather than presenting such devices as standalone diagnostics, PATHS suggests embedding them as risk escalation triggers in primary care, for example, sustained abnormalities in cardiorespiratory or inflammatory markers prompting targeted imaging or blood-based testing instead of immediate invasive evaluation.

This approach can protect primary care from unnecessary referrals while ensuring that subtle but persistent changes in risk profiles are not ignored. It also allows health systems to pilot wearables in defined high risk cohorts and to assess real world adherence, acceptability, and cost.

5.2. Breathomics and Paper-Based Microfluidics as Front Door Triage

Perioperative breathomics work by Wang *et al.* (2022) demonstrates that exhaled VOC signatures can differentiate lung cancer from controls with promising accuracy. When combined with paper based microfluidic tests for specific biomarkers (Ajikumar & Lei, 2024; Iqbal *et al.*, 2022), these platforms could function as a front door triage layer in tobacco cessation clinics or community screening camps.

Within a PATHS framework, such triage tests would be explicitly positioned at the primary care level, where they help teams prioritise individuals for more definitive imaging or liquid biopsy. Performance thresholds, cost per triaged patient, and referral capacity would be considered together to avoid overloading limited imaging and pathology resources.

5.3. Liquid Biopsy and Radiomics as Precision Back End

Liquid biopsy technologies for ctDNA and extracellular vesicles (EVs) are increasingly able to detect minimal disease, capture tumour heterogeneity, and monitor treatment response (Ge *et al.*, 2024; Hegade *et al.*, 2025). In parallel, radiomics and AI models are improving risk stratification and nodal staging in head and neck and other solid tumours (Valizadeh *et al.*, 2025; Huhulea *et al.*, 2025; Sahoo *et al.*, 2025).

In imaging constrained or pathology limited systems, these tools can serve as a precision back end, ensuring that scarce MRI, PET CT, and specialist referrals are directed to the highest risk patients identified through primary care triage layers. Within PATHS, they would be evaluated not only for their diagnostic performance but also for their compatibility with national cancer control strategies, reimbursement schemes, and workforce capacities.

6. Conclusion and Future Scope

The narrative review by Xu *et al.* (2025) convincingly shows that the biotechnology pipeline for early cancer detection is rich, diverse, and increasingly aligned with non-invasive, patient centred diagnostics. However, global experience with MCED tests, liquid biopsy, and AI reminds us that technology without thoughtfully designed pathways can fail to deliver meaningful population level gains and may even deepen inequities (Bamodu & Chung, 2024; Milner & Lennerz, 2024; Wade *et al.*, 2025).

The PATHS framework Performance for purpose, Access and affordability, Trust and ethics, Health system fit, and Sustainability offers a simple but actionable way for the journal's multidisciplinary audience to evaluate where and how to integrate biotechnological tools into real world primary healthcare pathways. Future research, including in India and other LMIC contexts, should co design and prospectively test PATHS guided early detection

programmes that combine breathomics, microfluidics, biosensors, liquid biopsy, organoids, and AI within existing national cancer control strategies.

Such work would directly advance the journal's mission to improve the organisation, delivery, and management of healthcare services and could help ensure that the promise of early cancer detection translates into earlier stage at diagnosis, better outcomes, and reduced inequities, rather than remaining a predominantly technological achievement.

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Authorship Contribution

M. Vijayasimha: Conceptualization of the PATHS framework, study design, critical intellectual input, manuscript drafting, and final approval; Logesh Babu: Literature review, framework structuring, data synthesis, and assistance in manuscript preparation; and Maitri Chakraborty: Review of evidence base, contextual analysis, manuscript editing, and validation of final content.

All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Ethical Approval

This manuscript is a conceptual and framework-based article and does not involve human participants, animals, clinical samples, or identifiable personal data. Therefore, ethical approval was not required.

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Conflict of Interest

The authors declare no conflict of interest related to this study.

Data Availability Statement

The authors declare that data sharing is not relevant to this article as no new data were generated or analyzed in this study.

Declarations

The authors declare that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All authors have contributed significantly and consent to publication in the present journal.

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