



Real-Time Biosensing of Cancer Therapy Response: Dynamic Biomarkers and the Shift Toward Feedback-Driven Precision Oncology

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Abstract

Cancer therapy response is still judged largely by tools that report late. Imaging and intermittent laboratory tests register treatment effects only once substantial structural change has accumulated, yet the molecular, metabolic, and immunological events that decide whether a therapy succeeds unfold within hours to days of the first dose. This review argues that dynamic biomarkers, monitored in real time or at high frequency by emerging biosensing platforms, supply a missing temporal axis in precision oncology. Two axes are already established: Genomics defines what to target, and imaging defines where disease resides. Biosensing defines when and how a tumor is responding. We synthesize the biological rationale for dynamic monitoring, define what “real-time” should and should not mean in oncology, and weigh the evidence for tumor-derived, metabolic, and immune biomarker sensing, separating what is clinically demonstrated (most notably circulating tumor DNA kinetics) from what remains preclinical. Rather than cataloging devices, we organize biosensing around the biological questions it answers and the decision points it could inform, then examine four barriers to adoption (sensor stability, biomarker standardization, data interpretability, and regulatory and ethical constraints) and identify the knowledge gaps that most limit progress. The core conclusion is that real-time biosensing is best understood not as a competing modality but as the temporal complement to genomics and imaging; its adoption is constrained less by sensor novelty than by the absence of standardized thresholds and prospective, interventional evidence that acting on dynamic signals improves outcomes.

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1. Introduction

Modern oncology is now quite good at matching a drug to its molecular target. It is far less good at answering a more basic bedside question: Is this treatment working right now? In routine care, clinicians infer response from radiographic imaging and periodic blood draws, instruments built to register slow, structural change in tumor burden rather than the fast biology that actually follows the first dose [1,2]. The result is a familiar and costly delay: An ineffective regimen can continue for weeks or months before resistance or non-response becomes visible on a scan, and during that time patients absorb the toxicity of a drug that was never going to help them, while a therapy that might have helped waits its turn [3].

This delay does not fall evenly across oncology; it is worst precisely where the field has advanced furthest. Targeted agents and immunotherapies produce responses that are heterogeneous, non-linear, and sometimes short-lived, a

difficulty that persists even where dedicated biomarker-enrichment strategies are used to select likely responders [4], and conventional imaging criteria, built primarily around lesion size, can still misread early immune infiltration or a burst of metabolic activity as stable or progressive disease [1]. Meanwhile, the biology that actually decides the outcome (target engagement, DNA damage, a shift in how the tumor burns fuel, immune activation, remodeling of the surrounding tissue) starts within hours and, in many cases, has already settled the trajectory of treatment long before any change is visible on a scan [5-8]. These early, decisive events happen largely out of view of a monitoring framework built around infrequent sampling and cumulative endpoints.

1.1 Rationale for a Temporal Axis in Precision Oncology

We treat this gap as a problem of temporal resolution, and the fix we propose is a third axis for precision oncology. Two axes are already well established: Genomic and

molecular profiling tell clinicians what to target, and imaging tells them where the disease is and how much of it there is. Neither one indicates, with any real precision, when and how a tumor is responding once treatment has started. Dynamic biomarkers, namely tumor-derived circulating material, metabolic signals, and immune mediators, carry exactly that temporal information, and biosensing is the technology that can make them accessible often enough to matter clinically. The organizing idea of this review is therefore to place biosensing alongside genomics and imaging as a temporal complement, not as a competing device category.

Most previous reviews treat biomarkers and sensor engineering as separate literatures, cataloguing one or the other rather than integrating them, and few address the harder questions: Which dynamic signals are actually actionable rather than merely measurable, how strong the clinical evidence really is, and where demonstrated capability ends and aspiration begins. This review therefore aims to (i) set out the biological rationale for dynamic, high-frequency monitoring; (ii) define real-time monitoring precisely enough that it does not overstate the readiness of the technology; (iii) weigh the available biosensing approaches and their supporting evidence by biomarker class; (iv) identify the barriers to adoption and the knowledge gaps that matter most; and (v) outline an integrative framework and research agenda for feedback-driven care. Underlying all five aims is a question that no single study can answer alone: Does matching response assessment to the true pace of tumor biology change how patients feel and how well their cancer is treated?

1.2 Scope and Literature Search

This is a narrative rather than a systematic review, and the search strategy is described here so that its coverage can be judged on its own terms. We searched PubMed/MEDLINE, Scopus, Web of Science, and Dimensions using terms for the clinical context (cancer, oncology, therapy response, treatment monitoring) combined with terms for measurement (biosensor, liquid biopsy, circulating tumor DNA, extracellular vesicles, cytokine, metabolic monitoring, wearable, implantable, real-time, and dynamic biomarker), and we screened the reference lists of retrieved articles for further sources. The core literature is peer-reviewed, English-language work published between 2020 and 2026, selected because it informs mechanism, temporal resolution, evidence quality, or translational barriers; work addressing diagnosis or screening without a therapy-response component, or device engineering without biological or clinical interpretation, was excluded. Where a claim rests on foundational results that predate this window, most notably the landmark studies that first established ctDNA kinetics as a tractable clinical signal [9,10], we cite them directly rather than only their more recent successors, because this historical grounding matters for understanding how the field arrived at its current, still narrow, base of clinical evidence. Beyond that, selection prioritized conceptual and evidentiary relevance over

exhaustive coverage, so we make no claim to completeness. Because narrative selection is inherently susceptible to bias, we state the strength of evidence explicitly throughout and keep demonstrated clinical utility separate from what remains preclinical or investigational.

2. From Static to Dynamic Biomarkers: A Conceptual Shift

Most of the biomarkers that oncologists currently use to judge treatment were never designed to capture change over time. They are measured at a handful of discrete time points and then read as if they were cumulative indicators of disease status [11]. Radiographic criteria, serum tumor markers, and histopathology are the standard examples: They are indispensable and they standardize how the field describes response, but they were built to report macroscopic outcomes rather than the biology that produces those outcomes, which leaves them poorly suited to the rapid, continuous change that modern therapies induce.

The problem concerns timing and specificity together. Imaging criteria depend on changes in tumor size or metabolic activity that can take weeks to appear, and in the meantime they can miss an early molecular response altogether [12]. Serum markers have their own blind spot: They are often insensitive to subtle or short-lived shifts and are confounded by tumor-burden heterogeneity and systemic inflammation, so they tend to give a delayed or ambiguous signal during precisely the window in which a clinical decision would matter [12]. Dynamic biomarkers behave differently; they evolve close in time to the therapeutic exposure itself and track ongoing tumor cell death, clonal selection, immune activation, and metabolic adaptation as they happen. Circulating tumor DNA (ctDNA) kinetics, for instance, can reveal rapid shifts in tumor-derived genetic material soon after treatment starts [9], often ahead of any radiographic change [10,13,14]. Cytokine flux moves on a similarly short timescale and tracks how engaged an immunotherapy actually is, while metabolic signals such as lactate, oxygen consumption, and local pH respond within minutes to hours [15].

It is worth being honest about where the field's confidence is earned and where it is not, because these two classes of biomarker are not validated to the same degree. That ctDNA dynamics track and often anticipate response is now well supported and broadly accepted [13,14]. The claim that real-time metabolic or immune signals are equally reliable, and that acting on them changes outcomes, rests on much thinner ground: Mostly preclinical work and observational series. The conceptual argument for dynamic monitoring applies uniformly across biomarker classes; the clinical argument, at the moment, is carried almost entirely by one mature example. The underlying problem is a mismatch in timing: Tumor biology evolves continuously, whereas clinical assessment occurs only intermittently. Figure 1 illustrates this shift from episodic to dynamic assessment.

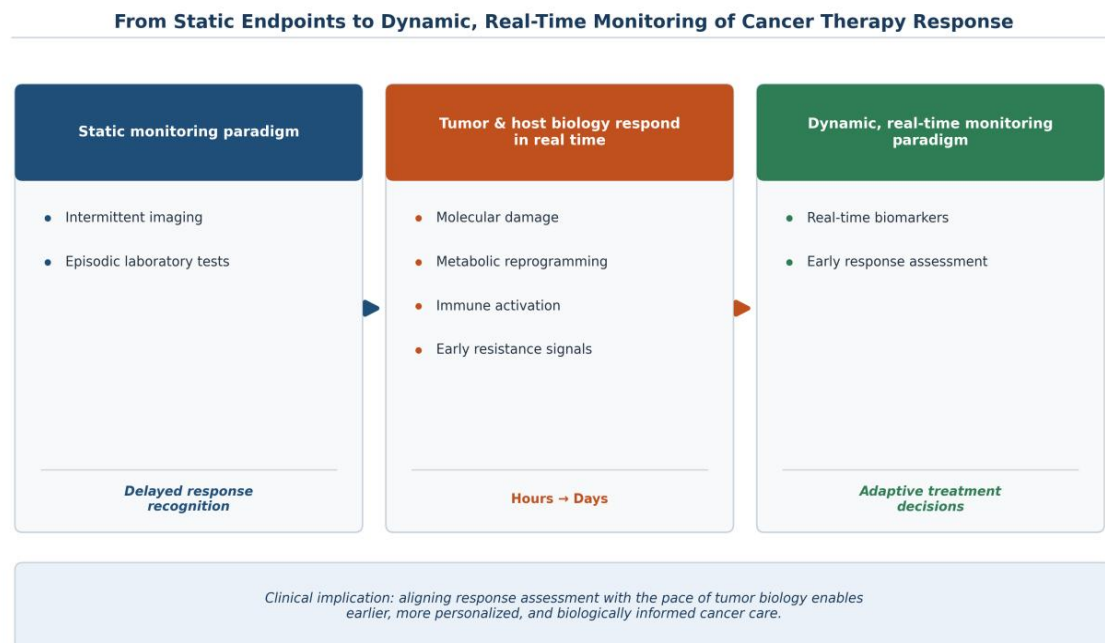


Figure 1. Moving from episodic, static assessment to a dynamic, real-time assessment. The tumor and host biology are responding within hours to days, while conventional imaging and laboratory testing capture the therapeutic response only after substantial change has accumulated. Real-time or high-frequency biosensing captures these dynamic signals directly, giving earlier insight into therapeutic engagement, resistance, or toxicity and supporting adaptive, precision-oncology decision-making. Original schematic prepared by the authors; not adapted from a copyrighted source.

3. Biological Basis of Therapy-Induced Dynamic Change

Cancer's response to therapy is neither instant nor uniform. It plays out as a sequence of molecular, cellular, and microenvironmental events that overlap in time, differ from one tumor region to the next, and, because they begin so soon after exposure, often decide the long-term

outcome before any change is visible. Grasping how these events are organized in time and space is the biological basis for dynamic biomarker monitoring, and it is also why sampling that is infrequent and averaged across the whole tumor is so easily misled. Figure 2 summarizes the mismatch between how fast therapy-induced biology actually moves and how slowly conventional assessment catches up.

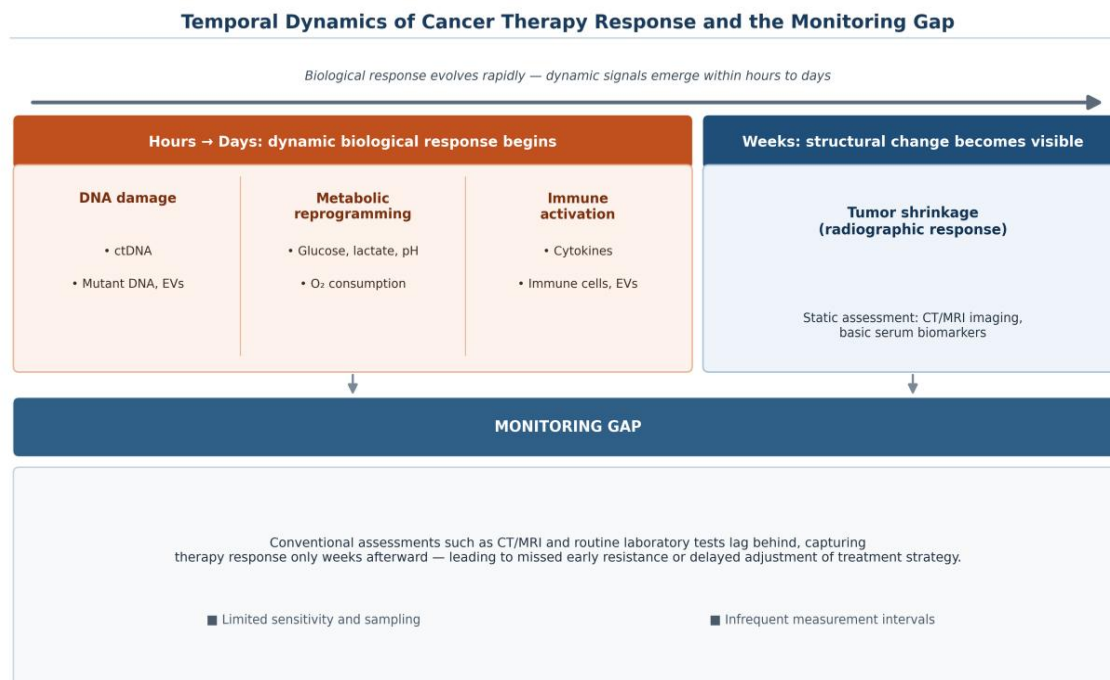


Figure 2. Timeline of cancer therapy response across biological and clinical timescales. Molecular damage, metabolic reprogramming, and immune activation all begin within hours to days of treatment, generating dynamic biomarkers — circulating tumor DNA, metabolic intermediates, and immune mediators — while conventional imaging and laboratory testing primarily detect the later structural change (tumor shrinkage) that follows, often weeks afterward. The resulting monitoring gap is where early indicators of response, resistance, or toxicity are missed. Original schematic prepared by the authors.

3.1 Early Molecular and Metabolic Responses

Most anticancer therapies produce a measurable biological effect within hours of exposure. Cytotoxic agents trigger DNA damage, replication stress, and apoptosis, while targeted agents act faster still, reshaping oncogenic signaling and shifting the balance between proliferation, survival, and stress responses [6]. These changes are typically accompanied by almost immediate metabolic reprogramming, as tumor cells adjust glucose uptake, oxidative phosphorylation, and redox balance under the new therapeutic pressure [8]. Because such shifts often precede any change in tumor size, they can signal that a therapy is engaging its target even while overall tumor burden appears unchanged. And because these responses are frequently transient, an infrequent assessment schedule is almost certain to miss the window in which the information would be most useful.

3.2 Immune Activation and Inflammatory Dynamics

The immune system is now recognized as an active determinant of response rather than a bystander. Immunotherapies target the immune system directly, but chemotherapy and radiotherapy also induce dynamic shifts in cytokine profiles, immune cell trafficking, and effector function through the release of tumor antigens, damage-associated molecular patterns, and inflammatory mediators [7]. These processes are time-dependent and often non-linear: Early activation can signal long-term benefit, whereas excessive or poorly controlled activation can signal toxicity or treatment failure, and cycles of activation, exhaustion, and re-adaptation may recur. Static imaging and single-time-point biomarkers are poorly suited to capturing dynamics on this timescale, which explains why discriminating between true progression and inflammation driven by therapy remains challenging, particularly under immune checkpoint inhibition, where immune-related adverse events are also difficult to distinguish from infection or other immune disorders using conventional tests [16].

3.3 Tumor Heterogeneity and the Emergence of Resistance

Spatial and temporal heterogeneity compound the problem. A single tumor may contain multiple subclones that respond differently to the same treatment, and genetic, epigenetic, and microenvironmental factors, such as hypoxia and nutrient deprivation, may favor resistant populations [17,18]. Resistance is typically a process rather than a single event: Weeks or months of reactivated signaling, altered drug transport, or metabolic adaptation often precede overt progression [19]. Because these changes vary across different regions of the tumor, bulk sampling and whole-tumor imaging cannot capture them. Together, these considerations point to the need for monitoring that is sensitive to both timing and biology, the case that the rest of this review sets out to make.

4. What “Real-Time” Should Mean in Oncology

In oncology, the term “real-time” is used loosely, and this looseness carries real risk: It can overstate how ready a

technology actually is and blur what is genuinely actionable in care [20]. Defining the term carefully is therefore not pedantry but a condition for translating the concept honestly. We take real-time monitoring to mean acquiring biological information on a timescale short enough both to reflect an ongoing treatment-induced process and to influence a decision. Two distinct modes fit this definition. Continuous monitoring provides uninterrupted or near-uninterrupted measurement, for example of physicochemical parameters in the tumor microenvironment or of circulating metabolic signals, and offers the temporal resolution that rapidly fluctuating processes require [15]. High-frequency monitoring instead relies on repeated measurements taken at short intervals, from minutes to days; it is not truly continuous, but it can still reveal trends that episodic testing would miss, as wearable cardiovascular monitoring has already shown [21].

Not all real-time data are actionable, however, and treating the two as interchangeable is probably the most common conceptual error in the field. For monitoring to matter clinically, its temporal resolution has to align with an actual decision point that could change management, such as early evidence of drug engagement, emerging resistance, or impending toxicity that would prompt continuing, modifying, or stopping treatment [22]. A rapid decline or rebound in ctDNA, a sustained immune-activation profile, or a persistent metabolic shift can inform this kind of early adaptation; a transient fluctuation that correlates weakly with outcome, or that has no validated threshold behind it, may be scientifically interesting but is clinically inert. Any claim made for a new monitoring platform should be held to this distinction between what is measurable and what is actionable.

A related distinction separates what is feasible today from what remains experimental. Several real-time or high-frequency strategies already show promise in preclinical models and early human studies, particularly for circulating and metabolic markers [14,15,23]. Implantable and wearable systems built for continuous measurement, however, remain largely investigational, whereas ex vivo and point-of-care platforms that enable frequent sampling are closer to implementation, although they still need further validation. Defining real-time monitoring honestly, in other words, means holding ambition against what the evidence currently supports; experience with real-time remote symptom monitoring during chemotherapy shows that patient and clinician experience, not technical capability alone, determines how such monitoring is used in practice [24].

5. Biosensing Platforms, Organized by Biological Question

Biosensing’s clinical value does not come from the novelty of the device itself; it comes from the capacity to interrogate biologically meaningful processes on a timescale clinicians can actually use. A clinically oriented framework, then, should not start by asking what engineering approach a sensor uses. It should ask which aspect of tumor or host biology the sensor monitors, why the timing of that signal matters, and how the sensor grants

access to it [25]. Table 1 lays out the major dynamic-biomarker classes on that basis, organized by the three

biological domains developed in the subsections that follow.

Table 1. Dynamic biomarkers relevant to real-time monitoring of cancer therapy response, organized by biological domain.

Domain	Biomarker class	Representative signals	Process reflected	Temporal sensitivity	Clinical relevance	Key limitations
Tumor burden dynamics (5.1)	Tumor-derived nucleic acids	ctDNA, mutant fragments	Tumor cell death, clonal dynamics	Hours-days	Early response or resistance	Low abundance; shedding variability
Tumor burden dynamics (5.1)	Extracellular vesicles	Tumor-derived EVs, exosomes	Intercellular signaling, stress	Hours-days	Tumor adaptation; TME interaction	Heterogeneous cargo; standardization
Metabolic & microenvironmental shifts (5.2)	Metabolic biomarkers	Lactate, glucose, pH, O ₂	Metabolic reprogramming, hypoxia	Minutes-hours	Early engagement or resistance	Confounded by systemic metabolism
Immune engagement & toxicity (5.3)	Immune mediators	Cytokines, chemokines, cell markers	Immune activation, inflammation	Hours-days	Immunotherapy response; toxicity	High variability; context-dependent
Multi-domain integration	Composite profiles	Integrated molecular-immune-metabolic	Coordinated response	Hours-days	Robustness; predictive accuracy	Integration & interpretation complexity

Abbreviation: TME, tumor microenvironment.

5.1 Tumor Burden Dynamics

The most direct index of response is a change in tumor burden itself, and molecularly that shows up as tumor-derived material entering the circulation. ctDNA kinetics capture cell death, clonal selection, and residual disease at a temporal resolution imaging simply cannot match: A rapid decline soon after treatment starts can indicate effective engagement, while early stabilization or a rebound may point to intrinsic resistance or underdosing [13]. Because these signals are dynamic and sometimes short-lived, how often clinicians sample is itself a determinant of clinical value [14]. Circulating tumor cells add a complementary, cell-based layer of information: Surface-biomarker profiling of circulating tumor cells (CTCs) has itself been used for real-time monitoring of therapy response, alongside cell-free ctDNA [26,27]. Extracellular vesicles, including exosomes, offer a related window onto ongoing cellular activity through their nucleic acid, protein, and metabolite cargo. Near-real-time tracking of molecular burden is made feasible by electrochemical, optical, and microfluidic platforms built for rapid, repeated measurement from small blood volumes; many are still under validation, but they already show how biosensing can complement imaging by revealing early molecular response [25].

5.2 Metabolic and Microenvironmental Shifts

Therapy also has an immediate effect on tumor metabolism and the surrounding microenvironment. Shifts in glycolytic activity, oxygen consumption, redox balance, and extracellular pH accompany cytotoxic stress, targeted inhibition, or immune attack, and these shifts are closely linked to whether a tumor is sensitive or resistant

[28]. Timing matters especially here, because these parameters change quickly and reversibly: A transient burst of reoxygenation or an abrupt change in lactate can indicate effective therapy, whereas persistent hypoxia or acidosis tends to drive resistance and immune suppression. Miniaturized electrochemical and optical sensors, including implantable and wearable formats, have already monitored pH, oxygen tension, and metabolic byproducts in preclinical and early clinical settings [15]. Long-term stability and deployment remain genuinely difficult, but this work shows how real-time metabolic monitoring could feed into adaptive therapy.

5.3 Immune Engagement and Toxicity

Immune mechanisms are central to both efficacy and toxicity in modern oncology. Checkpoint inhibitors, adoptive cell therapies, and combination regimens all drive rapid changes in cytokine signaling, immune-cell activation, and inflammatory mediators that unfold over hours to days and can precede both clinical benefit and immune-related adverse events [29]. In practice, timing is what separates productive immune engagement from dysregulated inflammation: An early cytokine surge can predict response, whereas sustained or excessive signaling can foreshadow toxicity, and conventional monitoring based on symptoms or late laboratory abnormalities routinely misses this window [16]. Multiplexed, high-frequency biosensors are designed to close that gap. Optical and electrochemical platforms have already measured cytokines with fast turnaround and high sensitivity; most cancer-specific applications remain investigational, but multiplex sensing in other acute inflammatory conditions, such as simultaneous IL-10 and C-reactive protein sensing to predict critical illness in

COVID-19, has already established that the approach is technically feasible [30].

6. Translational Evidence: What is Demonstrated, and How Strongly

Real-time biosensing is best described as biologically well supported but clinically uneven, and a fair review must weigh that evidence rather than simply summarize it. Preclinical models have repeatedly shown that therapy-induced molecular and metabolic changes can be captured shortly after exposure: Rapid shifts in tumor-derived nucleic acids, metabolic flux, and microenvironmental parameters follow cytotoxic agents, targeted therapy, and radiation alike [23]. These models consistently show that such signals change before any macroscopic regression, which is the source of the biological plausibility of the whole approach. They also reveal how transient many of these signals are, which is why measurement requires high temporal resolution to avoid misinterpretation.

Clinical evidence, however, narrows sharply to one mature example. Monitoring of ctDNA kinetics is by far the most advanced application: Multiple studies report that early changes in ctDNA correlate with later radiographic response and progression-free survival, often weeks ahead of imaging endpoints [10,14,31]. A similar, though less well-established, association with response and toxicity risk has been reported for immune biomarkers, namely dynamic changes in cytokines and immune mediators during immunotherapy [16,29]. In both cases, dynamic monitoring complements established assessment rather than replacing it. The critical caveat, arguably the field's biggest methodological weakness, is that most of this evidence is correlative and observational, not interventional. We know dynamic biomarkers track outcome; we do not know that acting on them earlier actually improves outcome, because prospective trials that randomize patients to biomarker-guided adaptation are still scarce. Several other limitations stack on top of that. Clinical validation is concentrated in a small number of tumor types and biomarker classes, so how well it generalizes is genuinely uncertain. Standardized thresholds for what count as a clinically meaningful change are largely missing, which leaves interpretation up to whoever is running the study. Even for ctDNA, real-time assessment usually plays a supporting role in treatment selection rather than a decisive one [32]. And publication bias probably inflates how ready the field looks, since a successful proof-of-concept is published far more reliably than a null result. Biosensing has genuinely improved early response assessment. Whether it becomes standard practice depends on evidence that does not exist yet: Prospective proof that biomarker-guided adaptation actually changes what happens to patients.

7. Integration into Precision Oncology: The Temporal Axis

Biosensing's clinical impact will hinge on integration, not on how well it performs as a standalone measurement. For biosensing-derived data to be useful, it needs to

complement the modalities oncology already relies on, inform decisions at the moments that matter, and support adaptation without adding complexity or uncertainty to care [25]. That is the logic behind the framework this review proposes. Precision oncology already runs on two axes: Genomic profiling identifies actionable alterations and tells clinicians what to target [33], and imaging shows where the disease is and how much of it there is. Dynamic biomarker monitoring adds a third, temporal axis, capturing when and how the tumor and host are responding once therapy has begun. Read this way, the three axes are complementary rather than competing: Genomics selects the therapy, imaging localizes and stages the disease, and biosensing reports whether the therapy is working in time to change course.

In practice, this temporal axis matters most within clinical decision support. Continuous or high-frequency biosensing produces longitudinal data that differ fundamentally from an episodic result [34]; when processed and contextualized appropriately, these data streams can flag early engagement, emerging resistance, or impending toxicity, and can be combined with genomic and imaging parameters to support earlier and more confident decisions. Such systems must prioritize interpretability, so that their output serves as guidance rather than an additional data burden for the clinician. The framework also helps resolve an ambiguity that clinicians currently face: Discordance between a molecular response and an apparently stable scan becomes easier to interpret once the temporal trajectory is visible. The most forward-looking use case is adaptive management, in which an early favorable response supports de-escalation to limit toxicity, and an early non-response prompts escalation or a switch in therapy. Fully automated closed-loop control is still conceptual in oncology, but biosensing supplies the feedback data on which more responsive, individualized adaptation would depend [35].

8. Why Real-Time Biosensing is not Yet Standard of Care

Real-time biosensing is not yet routine, despite its conceptual appeal and growing interest in the field. This gap reflects a combination of engineering, biological, and clinical barriers, and each needs careful examination to calibrate expectations and direct future effort.

8.1 Sensor Stability and Reproducibility

Keeping a sensor's signal reliable over clinically relevant timeframes is a central engineering obstacle. Sensors operating in complex biological media must contend with variable temperature, pH, and composition, and are prone to biofouling, material degradation, and signal drift, problems that accumulate in systems built for continuous or repeated use. Advances in nanomaterials, surface chemistry, and encapsulation have improved performance under controlled conditions, but reproducibility across patients and care settings remains inconsistent [36]. Without robust long-term stability and dependable calibration, clinical utility remains inherently limited.

8.2 Biomarker Variability and Standardization

Biological variability is an equally formidable barrier. Many dynamic biomarkers fluctuate for reasons unrelated to treatment efficacy, including circadian rhythms, comorbidities, and ordinary inter-individual differences in metabolism or immune function [37]. Tumor heterogeneity also means that biomarker release can vary by site and disease stage. Standardized thresholds for what counts as a meaningful change are largely absent, which makes it difficult to separate a clinically relevant signal from background noise. Consensus on which biomarkers matter most, how often to measure them, and how to interpret a change is a prerequisite for adoption, and its absence is arguably a greater constraint on the field than the limitations of any individual sensor.

8.3 Data Volume and Interpretability

High-frequency monitoring generates more longitudinal data than traditional interpretation frameworks were built to handle, and this volume can overwhelm clinicians rather than inform them. Signal noise, transient fluctuations, and interdependent biomarker dynamics all complicate interpretation, so translating these data effectively depends on trend analysis, anomaly detection, and decision rules that have been clinically validated. This is where artificial intelligence and machine-learning methods are beginning to earn a role: When trained appropriately, they can filter noise, flag temporal patterns that a human reader might miss, and highlight deviations linked to response, resistance, or toxicity, without displacing clinical judgment [38-40]. Interpretability has to come first, because clinician trust depends not only on accuracy but also on how clearly and reliably the output is presented; an opaque or overly complex model will not be adopted, however well it performs [39].

8.4 Regulatory and Ethical Considerations

Devices designed to impact treatment decisions must meet high standards of safety, accuracy, and clinical effectiveness, and wireless systems present unique issues of data security, privacy, and informed consent, especially when the data is incorporated into a wider digital health network [41]. There is an ethical dimension too: Continuous monitoring carries a psychological burden of its own, and there is a real risk of over-intervening on the basis of a signal that has not been validated. None of this gets resolved without transparent governance, rigorous validation, and alignment across regulators.

That alignment is still mostly aspirational. Regulatory frameworks for liquid-biopsy biomarkers remain incomplete [42]. Formal pathways for validating a biomarker's clinical meaning, such as the FDA's Biomarker Qualification Program and the EMA's biomarker qualification procedure, already exist, but only a small fraction of candidate biomarkers has so far navigated them successfully [43,44], and dynamic, sensor-derived signals have barely begun to enter that pipeline. There is a reasonable case for building biosensing endpoints into Phase II and III trial designs earlier, rather than treating them as an afterthought once a

drug is close to approval. Doing so could give regulators the prospective, standardized evidence base that dynamic monitoring currently lacks, and would let industry help drive standardization instead of waiting for it. Coordinated engagement between drug developers and regulators on trial-embedded biosensing is a large part of what would let the field move past its current, mostly exploratory status [42]. Collectively, these barriers are why biosensing remains an emerging technology rather than an established one; acknowledging that is not a concession, it is the realistic starting point for making progress.

9. Knowledge Gaps and Future Directions

The field's trajectory runs from single-analyte measurement toward integrated, adaptive systems, but its most pressing needs are evidential at least as much as technological. One priority is multiplexed dynamic panels that capture complementary tumor and host biology together: No single biomarker represents the full complexity of a response, and combining tumor-derived signals with metabolic and immune indicators improves robustness by not relying on any one fluctuating signal, and may even reveal coordinated patterns that a single-analyte approach would miss [45]. Advances in miniaturization, surface chemistry, and signal discrimination are increasingly making that kind of integrated measurement possible [46], though which biomarker combinations are clinically optimal is still an open question.

As the data become more complex, AI and machine-learning methods are expected to help interpret biomarker trajectories, identifying temporal patterns, filtering noise, and flagging deviations related to response, resistance, or toxicity, without taking over clinical judgment. Beyond interpretation, similar methods could plausibly be trained to calibrate the sensors themselves: Correcting for signal drift over time, filtering background noise at the source, and improving sensitivity for low-abundance signals such as early ctDNA shedding, tasks that bear directly on the stability problems described in Section 8.1. In either role, the value of these methods will depend on transparency, explainability, and rigorous validation against real outcomes across diverse datasets [40]. The most forward-looking application, framed cautiously, is closed-loop or adaptive therapy, in which biological feedback drives iterative adjustment of drug, dose, or schedule [35]. Full automation is unlikely in the near future, given the biological complexity and safety stakes involved, but semi-adaptive strategies under clinician oversight, such as dose modification or a treatment switch guided by early molecular response, are realistic and mirror feedback-driven models already used elsewhere in medicine.

Set against these opportunities, the gaps that most limit the field are specific enough to structure a research agenda. The most important is the near-absence of prospective, interventional trials showing that biomarker-guided adaptation improves outcomes rather than merely tracking them; without that evidence, biosensing remains adjunctive by default. The second is standardization: Without agreed, auditable thresholds for what counts as a

meaningful change, comparing studies or securing regulatory acceptance is essentially impossible. The third is generalizability beyond the small number of tumor types in which most validation has taken place. The fourth is equity of access. Prioritizing interventional evidence and standardization would advance the field more than another round of sensor demonstrations.

10. Conclusion

Cancer therapy response is still judged by tools that report late, even though the biology that determines success moves fast. This review has argued that the solution is not another standalone modality but a missing dimension. Dynamic biosensing supplies the temporal axis of precision oncology, complementing the genomic axis that defines what to target and the imaging axis that defines where the disease is, by showing, close to real time, whether and how a tumor is responding. Framed this way, the central question for the field is not whether faster measurement is possible, since ctDNA kinetics have already shown that it is, but whether acting on faster measurement actually improves care. The evidence so far is strong on biological plausibility and correlation, and weak on the interventional proof that would make dynamic monitoring decisive rather than adjunctive. The main constraint, in other words, is not sensor novelty but the lack of standardized thresholds and prospective trials, together with the engineering robustness, interpretability, and governance that responsible deployment demands. Resolving these would turn precision oncology from a largely static, pre-treatment paradigm into a feedback-driven one that keeps adapting to each patient's disease as it unfolds.

Declarations

Ethics Approval

Not applicable.

Consent for Publication

Not applicable.

Availability of Data and Materials

Not applicable. No datasets were generated or analyzed in the preparation of this review.

Competing Interests

The authors declare that they have no competing interests.

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Grammarly, an AI-powered writing assistant, was used during preparation of this manuscript for language editing and grammar and spell-checking only. It was not used to generate ideas, analyze data, or interpret results. The authors reviewed and edited every suggested change and take full responsibility for the content of this publication.

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