

Nanobiosensors for Early Detection of Obesity-Associated Metabolic Dysregulation: Advances in Non-Invasive Diagnostics

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ABSTRACT

Obesity is a chronic, relapsing disease characterized by complex perturbations in glucose homeostasis, lipid metabolism, adipokine secretion, inflammation and organ-specific function. These changes often precede overt clinical complications by years, creating an important window in which early detection and intervention could prevent progression to type 2 diabetes, fatty liver disease and cardiovascular events. Conventional diagnostics rely on intermittent blood tests that are invasive, inconvenient and poorly suited to continuous risk stratification. Nanobiosensors, integrating nanostructured transducers with selective biorecognition elements, are emerging as powerful tools for sensitive, real-time and non-invasive monitoring of metabolic biomarkers in easily accessible biofluids such as sweat, saliva, tears, urine and exhaled breath. This review summarizes the pathophysiological basis of obesity-associated metabolic dysregulation and the rationale for early, non-invasive detection. It then discusses design principles and transduction mechanisms of nanobiosensors, including electrochemical, optical and plasmonic platforms. Advances in sampling interfaces for sweat, saliva, tears, breath and urine are examined, together with state-of-the-art nanobiosensors for glucose, lipids, adipokines and inflammatory markers, including multiplex and wearable systems. We highlight integration with mobile health technologies, data analytics and multimodal sensing, and critically examine challenges in analytical validation, clinical translation, regulation and equity. Finally, future directions are outlined for personalized, continuous metabolic risk monitoring using nanobiosensors as a cornerstone of precision obesity care.

Keywords: Nanobiosensors; Obesity; Metabolic dysregulation; Non-invasive diagnostics; Wearable sensors

INTRODUCTION

Obesity represents far more than an excess of adipose mass; it is a systemic disorder of energy balance and endocrine function that unfolds gradually over many years. Adipose tissue expansion in response to chronic caloric surplus is initially adaptive, but sustained hypertrophy and hyperplasia precipitate hypoxia, low-grade inflammation and extracellular matrix remodeling[1-3]. These local changes propagate systemically through altered release of free fatty acids, adipokines and cytokines, which disrupt insulin signaling, hepatic lipid handling and vascular homeostasis. The result is a spectrum of obesity-associated metabolic dysregulation encompassing impaired glucose tolerance, hyperinsulinemia, dyslipidemia, non-alcoholic fatty liver disease and early cardiovascular dysfunction[4-6].

Critically, these abnormalities emerge long before classical diagnostic thresholds are crossed. Individuals may exhibit postprandial dysglycemia, subtle changes in triglyceride-rich lipoproteins, early adipokine imbalance or modest increases in inflammatory markers while still meeting "normal" or "borderline" laboratory criteria. Over time, compensatory mechanisms fail and frank type 2 diabetes, overt NAFLD or clinical cardiovascular disease appear[7, 8,9-13]. The latency between early biochemical changes and symptomatic disease provides an opportunity for preventive intervention, provided that such changes can be detected and monitored with sufficient sensitivity and temporal resolution.

Current clinical practice is dominated by episodic blood-based tests fasting glucose, HbA1c, lipid panels, liver enzymes and high-sensitivity C-reactive protein typically measured annually or less frequently in at-risk individuals. While valuable, these snapshots provide limited insight into dynamic patterns such as glycemic excursions, meal-related triglyceride peaks or day-to-day fluctuations in inflammatory tone[9,14-20].

Moreover, venipuncture is invasive, inconvenient and often underutilized outside formal healthcare settings. Point-of-care finger-prick glucose meters partially mitigate these limitations for patients with diabetes, but they remain invasive, focus on a single biomarker and are seldom used proactively in individuals with obesity but without diagnosed diabetes[9,21-27].

Non-invasive, continuous or high-frequency monitoring of metabolic markers could transform obesity management. Early detection of dysglycemia, increasing triglycerides, perturbations in adipokine ratios or subtle declines in insulin sensitivity could trigger timely lifestyle modification or pharmacotherapy long before irreversible organ damage occurs[10, 28-34]. Continuous sensing also captures intra-individual variability in response to specific foods, sleep patterns and physical activity, revealing personalized triggers for dysregulation that are invisible to sporadic testing. Integrating such data into digital health platforms and decision-support tools could support tailored, adaptive interventions at scale[10, 11,35-40].

Nanobiosensors are particularly well suited to this task. By incorporating nanostructured materials such as metal nanoparticles, carbon nanotubes, graphene, nanozymes, or metal-organic frameworks into transducers, it is possible to dramatically increase surface area, electron-transfer efficiency, and signal amplification [12,41-43]. This translates into higher sensitivity, lower detection limits and faster response times for both electrochemical and optical biosensors. Recent reviews emphasize that nanomaterial-enabled wearable and non-invasive sensors can achieve clinically relevant performance in sweat, saliva and other biofluids that were previously considered analytically challenging[12,44-50].

The obesity field can leverage these advances. Sweat contains electrolytes, lactate, glucose, uric acid and, under some conditions, small proteins and cytokines that mirror blood levels; saliva carries hormones, cytokines and metabolic end products; tears and exhaled breath contain volatile and non-volatile molecules linked to oxidative stress and glucose metabolism[13,51-54]. Urine is a particularly rich reservoir of metabolites reflecting global metabolic state and has recently been highlighted as a promising source of non-invasive biomarkers for obesity-related metabolic diseases. Nanobiosensors that operate on these fluids, especially in wearable formats, can provide continuous or on-demand information with minimal user burden[13,55-60].

Several classes of biomarkers are especially relevant to obesity-associated dysregulation. Glucose dynamics are central, as many patients with obesity will progress along the continuum from normoglycemia to impaired glucose tolerance and eventually diabetes[14,61-66]. Non-invasive glucose sensing via sweat, interstitial fluid or other matrices using nanomaterial-enhanced electrodes and optical probes is a major research area and has demonstrated promising correlation with blood glucose in controlled settings. Lipid-related markers, including triglycerides, cholesterol and free fatty acids, are also important for cardiovascular risk; paper-based plasmonic nanosensors and other nanostructured devices have been developed to detect these analytes in small sample volumes suitable for near-patient testing[14,67-73].

Adipokines such as leptin, adiponectin and resistin serve as endocrine links between adipose tissue and systemic metabolism, and their ratios have been proposed as markers of insulin resistance and fatty liver disease[15, 16,74-79]. Nanobiosensors capable of multiplexed detection of these proteins in serum or alternative fluids using graphene-based immunosensors, aptamers or molecularly imprinted polymers are now emerging. Inflammatory and oxidative stress markers, including cytokines and reactive oxygen species-related metabolites, round out a panel that can map the metabolic and inflammatory landscape of individuals with obesity[15,80-84].

To be useful in practice, sensors must be non-invasive or minimally invasive, robust in real-world conditions and compatible with user-friendly form factors such as skin patches, textiles, oral appliances or handheld readers. Recent progress in flexible, stretchable electronics and textile integration suggests that such devices are feasible and can be connected to smartphones for real-time data transmission and analysis[17,85-89]. Against this backdrop, nanobiosensors sit at the intersection of materials science, analytical chemistry, digital health and metabolic medicine, offering a plausible route toward early detection and continuous monitoring of obesity-associated dysregulation. The following sections explore their design principles, non-invasive sampling strategies, specific applications to key biomarkers, and the path toward clinical implementation.

2. Design Principles and Transduction Mechanisms of Nanobiosensors for Metabolic Biomarkers

Nanobiosensors integrate a recognition element that binds a specific analyte, a transducer that converts this binding event into a measurable signal and a nanostructured interface that enhances performance. For obesity-related diagnostics, the dominant platforms are electrochemical, optical and plasmonic sensors, often built on flexible substrates compatible with wearables[18, 19,90-94].

Electrochemical nanobiosensors rely on measuring current, potential or impedance changes resulting from analyte interactions at the sensor surface. Nanostructured electrodes based on gold nanoparticles, carbon nanotubes, graphene or metal-organic frameworks provide high surface area, fast electron transfer and tunable functionalization sites[20,95-96]. Biorecognition elements such as enzymes, antibodies, aptamers or molecularly imprinted polymers are immobilized on these nanostructures, translating binding events into redox reactions or interfacial impedance changes. For glucose, non-enzymatic nanocatalysts and enzyme-nanomaterial hybrid architectures have been extensively studied to improve stability and reduce oxygen dependence[21].

Optical and plasmonic sensors exploit changes in light absorption, fluorescence, surface plasmon resonance or scattering induced by analyte binding. Nanostructured metal films, nanorods and photonic crystals concentrate electromagnetic fields at the sensor surface, amplifying subtle refractive index changes [22]. A recent design of a gold-coated photonic crystal fiber SPR sensor for metabolic disorders illustrates how nanostructured optics can achieve high refractive-index sensitivity suitable for detecting small changes in biofluid composition. Paper-based plasmonic nanosensors that use nanoparticle aggregation or localized SPR shifts enable colorimetric or spectroscopic readouts of multiple metabolic analytes from microliter-scale samples [22].

Graphene and related two-dimensional materials occupy a special place due to their exceptional electrical conductivity, mechanical flexibility and large surface-to-volume ratio. Graphene-based field-effect transistors and laser-scribed graphene electrodes have been developed for highly sensitive, label-free detection of proteins and small molecules in non-invasive formats. Functionalization with specific capture probes allows these devices to quantify adipokines, cytokines or metabolites in complex matrices with minimal sample preparation [23].

Across modalities, selectivity and stability are key challenges. Aptamers and molecularly imprinted polymers provide alternatives to antibodies, with improved robustness and tunable affinity for small-molecule metabolites [24]. Nanozymes—nanomaterials with enzyme-like catalytic activity offer another promising route for stable, low-cost signal amplification in electrochemical and colorimetric sensors. Antifouling coatings, such as zwitterionic polymers and hydrogels, are essential to maintain performance in protein-rich biofluids [24]. Finally, the interface between sensor and skin or mucosa demands careful engineering. Flexible substrates, strain-tolerant interconnects and microfluidic structures for sample collection and conditioning are increasingly integrated into nanobiosensor platforms, allowing reliable operation during motion and long-term wear [25]. Signal processing and wireless communication modules complete the system, enabling continuous streaming of metabolic data to mobile devices or cloud platforms for analysis.

3. Non-Invasive Biofluids and Sampling Interfaces: Sweat, Saliva, Tears, Breath and Urine

Non-invasive or minimally invasive sampling is fundamental to user acceptance and feasibility of continuous monitoring in obesity. Several biofluids are particularly attractive for nanobiosensing: sweat, saliva, tears, exhaled breath and urine. Each has distinct advantages and constraints that influence sensor design [26].

Sweat has received the most attention for wearable biosensing because it can be accessed continuously through the skin without breaching the barrier. It contains electrolytes, lactate, glucose, urea, uric acid and trace amounts of hormones and cytokines, reflecting both systemic and local physiology [27]. Microfluidic patches and flexible electrochemical sensors equipped with nanostructured electrodes now permit simultaneous monitoring of multiple sweat analytes, including glucose and lactate, with on-skin readout. Challenges include low and variable sweat rates, contamination from skin, and complex correlations between sweat and blood concentrations that may depend on temperature, hydration and exercise [27].

Saliva is another promising biofluid. It is easy to collect, contains hormones such as cortisol and ghrelin, cytokines, antibodies, uric acid and various metabolites and can mirror systemic metabolic and inflammatory status [28]. Nanobiosensors built into mouthguards, dental appliances or simple paper-based strips can measure salivary analytes relevant to obesity, such as glucose, uric acid and inflammatory markers, without needle-based sampling. The main barriers are variable flow rates, effects of food and oral hygiene and potential degradation of biomolecules by salivary enzymes [28].

Tears offer a more stable microenvironment with lower protein content and have been explored for glucose, electrolytes and stress biomarkers. Soft contact lens sensors with embedded nanostructured electrodes or optical transducers can, in principle, provide continuous tear-based monitoring, although user comfort, calibration and long-term safety remain active research topics [29]. Breath analysis focuses on volatile organic compounds such as acetone, isoprene and ethanol, which can reflect fat oxidation, oxidative stress and metabolic flexibility. Nanomaterial-based chemiresistors and optical sensors have been developed to detect breath acetone as a surrogate of fat metabolism, offering a completely non-invasive means of interrogating metabolic state [29].

Urine occupies a distinct niche. It is readily obtainable, non-invasive and rich in metabolites that integrate metabolic processes over time. Recent metabolomic studies have identified urinary signatures associated with obesity, insulin resistance and NAFLD, prompting interest in urinary biomarkers for early detection of obesity-related metabolic diseases [30]. Nanobiosensors for point-of-care urine testing, including paper-based plasmonic devices and nanoparticle-enhanced lateral flow assays, can detect panels of metabolites such as glucose, uric acid, creatinine and microalbumin, providing complementary information to continuous wearable sensing [30].

Interstitial fluid accessed via microneedle arrays represents a minimally invasive compromise, but strictly non-invasive approaches focus on the other fluids [31]. For all these matrices, the relationship between local biofluid concentration and systemic status can be complex and may require calibration models that incorporate factors such as temperature, sweating rate or flow dynamics. Combining biosensors with integrated microfluidics to control sampling and with algorithms that correct for confounders will be essential to translate non-invasive measurements into clinically actionable metrics of metabolic dysregulation [31].

4. Nanobiosensors for Key Obesity-Related Biomarkers: Glucose, Lipids, Adipokines and Inflammation

Among obesity-associated biomarkers, glucose is the most intensively studied, both due to its central role in diabetes and because it is relatively abundant and well characterized. Nanomaterial-assisted glucose biosensors

exploit metal nanoparticles, carbon nanotubes, graphene and nanozymes to enhance sensitivity and reduce response times in non-invasive matrices such as sweat, saliva and tears[32]. Wearable glucose sensors based on metallic nanomaterials and flexible electrodes have shown promising correlation with blood glucose under controlled conditions, and multi-analyte devices now combine glucose with lactate, sodium and other markers to provide a richer picture of metabolic status and hydration[32].

Lipid-related biomarkers, including triglycerides, total cholesterol, HDL and LDL, are more challenging to measure non-invasively due to their hydrophobicity and lower concentrations in many alternative biofluids[33]. Nevertheless, nanoparticle-based plasmonic and electrochemical sensors capable of detecting cholesterol and triglycerides from finger-prick blood or minimally invasive samples have been reported, and paper-based plasmonic nanosensors can simultaneously quantify glucose, cholesterol, uric acid and lactate with micromolar detection limits suitable for early metabolic screening. Translating such platforms into fully non-invasive matrices, for instance, via urinary or sweat lipid metabolites, remains an active area of research[33].

Adipokines offer a more direct readout of adipose tissue function. Leptin reflects fat mass and satiety signaling, while adiponectin is inversely related to insulin resistance and cardiovascular risk; the adiponectin-leptin ratio has been proposed as a sensitive marker of metabolic health and NAFLD[34, 35]. Nanobiosensors using laser-scribed graphene electrodes, aptamers and molecularly imprinted polymers have been developed for simultaneous detection of leptin and adiponectin, demonstrating low detection limits and multiplex capability in small serum samples. Incorporating these sensors into minimally invasive or ex vivo devices could enable routine adipokine profiling in obesity clinics, potentially preceding more expensive imaging for fatty liver or visceral fat quantification[36].

Low-grade inflammation is another hallmark of obesity-associated dysregulation. Cytokines such as IL-6, TNF- α and CRP, as well as oxidative stress markers, contribute to insulin resistance and vascular injury[4]. Nanostructured immunosensors capable of detecting these proteins in saliva, sweat or finger-prick blood leverage high surface area, enhanced mass transport and signal amplification strategies such as nanoparticle labels and nanozymes[37]. While absolute concentrations in non-invasive fluids may be low, trends over time and relative changes in response to lifestyle or pharmacological interventions may still be informative as personalized indicators of inflammatory burden.

The next step is true multiplexing. Multi-channel nanobiosensing platforms are being designed to simultaneously monitor panels of metabolic and inflammatory markers, for example combining glucose, lactate, uric acid, electrolytes and selected cytokines within a single sweat patch or saliva device[38]. Such platforms align well with the multifactorial nature of obesity and metabolic syndrome, enabling composite indices that better capture an individual's risk trajectory than any single biomarker alone.

5. Wearable and Portable Nanobiosensing Systems for Early Warning and Continuous Monitoring

The translation of nanobiosensors from laboratory demonstrations to clinically relevant tools hinges on their integration into wearable or portable systems that can operate reliably in everyday life. Rapid progress in flexible electronics, low-power microcontrollers and wireless communication has enabled skin-mounted patches, textiles, wristbands and oral devices that continuously collect biofluid samples, perform on-board sensing and transmit processed data to smartphones or cloud servers[39].

Sweat-based wearable platforms are at the forefront of this movement. Microfluidic patches molded from soft elastomers channel sweat from the skin into sensing chambers, where nanostructured electrochemical electrodes detect metabolites and electrolytes. Motion-tolerant designs, including stretchable interconnects and flexible nanoengineered sensing layers, mitigate signal artifacts during physical activity[40]. Advanced systems incorporate multi-parameter sensing, signal conditioning, digital filtering and Bluetooth transmission into compact modules powered by thin-film batteries or energy harvesting devices. Such devices could accompany patients through daily activities, capturing how real-world behaviors and environments influence metabolic markers[40].

Portable, non-wearable nanobiosensors also have a role, particularly for home or clinic-based spot testing. Paper-based and lab-on-chip devices that use plasmonic nanoparticles, graphene electrodes or nanozyme labels can be read visually, with simple readers or via smartphone cameras, enabling low-cost screening of urine, saliva or capillary blood for metabolic risk markers[41]. For example, a paper-based plasmonic nanosensor capable of detecting glucose, cholesterol, uric acid and lactate could serve as a rapid assessment tool in primary care or community health settings, prompting further evaluation when abnormal patterns are observed[41].

These hardware advances must be matched with sophisticated data handling. Raw signals from nanobiosensors are affected by environmental conditions, device aging and user behavior. Algorithms for baseline correction, artifact removal and calibration are essential, and machine learning models can learn individualized relationships between non-invasive measurements and clinical outcomes, improving accuracy over time[42]. Integration with mobile health platforms allows visualization of trends, automated alerts for emerging risk and closed-loop interaction with digital therapeutics or coaching programs. For instance, a system might detect increasing postprandial glucose excursions and rising sweat lactate over weeks, prompting targeted dietary counseling or adjustment of pharmacotherapy[42].

Importantly, user-centered design is critical. Devices must be comfortable, unobtrusive and compatible with varied skin types, climates and cultural norms. Battery life, waterproofing and ease of use influence adherence. For obesity and metabolic disease, where long-term behavior change is central, sensors that integrate seamlessly into daily life are more likely to support sustained engagement and meaningful outcomes than bulky or intrusive systems[43].

Ultimately, wearable and portable nanobiosensing platforms can shift the diagnostic paradigm from episodic, clinic-based testing to continuous, context-aware monitoring, enabling earlier detection of metabolic dysregulation and more agile, personalized intervention.

6. Clinical Validation, Regulatory Pathways and Implementation Challenges

Despite impressive technical advances, the clinical impact of nanobiosensors for obesity-related metabolic dysregulation will depend on rigorous validation, regulatory approval and thoughtful implementation[44]. Analytical performance must first be established, including limits of detection, linear ranges, specificity, precision and stability in relevant biofluids and under realistic conditions of temperature, motion and storage. Comparisons against gold-standard laboratory assays in blood and other fluids are needed to define calibration relationships and assess whether non-invasive measurements can achieve clinically acceptable accuracy and reliability[44].

Clinical validation extends beyond correlation with single-time-point measurements. For early detection and risk stratification, the key question is whether patterns in non-invasive sensor data such as trends in sweat glucose, urinary metabolite panels or salivary inflammatory markers, predict clinically important outcomes, including progression from normoglycemia to prediabetes, onset of NAFLD or incident cardiovascular events[45]. Prospective cohort studies and interventional trials incorporating nanobiosensors alongside standard assessments will be required to quantify added predictive value and to refine interpretation of complex, high-frequency data streams.

Regulatory pathways for nanobiosensors are evolving. Devices that provide diagnostic information or guide therapy will typically be classified as medical devices and must meet stringent requirements for safety, manufacturing quality and performance[46]. For wearable systems that include software components, cybersecurity and data privacy become integral parts of regulatory evaluation. Regulatory agencies are paying increasing attention to AI and machine-learning components embedded in diagnostic systems, which must be transparent, robust and monitored for drift[46].

Implementation in clinical practice and public health settings poses further challenges. Clinicians and patients will need clear guidelines on when and how to use nanobiosensor data. For example, what threshold or pattern of non-invasive glucose and adipokine changes should trigger more intensive testing or treatment [47]. How should conflicting signals between conventional lab tests and sensor data be resolved? Health systems must develop workflows and digital infrastructure to receive, process and act on continuous data, avoiding alert fatigue while capitalizing on early-warning potential[47].

Economic considerations are also important. Manufacturing nanostructured sensors, especially in flexible and disposable formats, must be cost-effective at scale. Reimbursement mechanisms for wearable diagnostics are still emerging and may depend on demonstrating cost savings through reduced complications or hospitalizations[48]. There is a risk that advanced nanobiosensing technologies could initially be accessible mainly to affluent populations, potentially widening disparities in obesity-related outcomes. Proactive efforts to design low-cost, robust platforms and to test them in diverse settings will be essential to promote equitable access.

Finally, users' perceptions of continuous metabolic monitoring must be considered. For some, real-time feedback may be empowering and motivating; for others, it may provoke anxiety or data overload. Ensuring that nanobiosensor deployment supports autonomy, informed choice and patient-clinician partnership will be as important as refining the underlying materials and electronics.

7. Future Directions: Toward Precision Metabolic Phenotyping and Personalized Intervention

As nanobiosensor technologies mature, their role in obesity management is likely to shift from isolated measurement of individual biomarkers to integrated, precision metabolic phenotyping. Continuous or frequent monitoring of glucose, lactate, uric acid, electrolytes, adipokines and inflammatory markers through non-invasive platforms can generate rich multi-dimensional datasets that capture how each individual's metabolism responds to diet, sleep, stress and physical activity.

Combining these data with information from wearable motion trackers, heart rate monitors and environmental sensors will enable the construction of personal "metabolic fingerprints." Machine learning models trained on large datasets could identify clusters of individuals with similar dynamic profiles, revealing subtypes of obesity characterized by predominant insulin resistance, dyslipidemia, inflammatory activation or impaired metabolic flexibility. This stratification can guide choice and titration of therapies, for example prioritizing GLP-1 receptor agonists in those with marked postprandial dysglycemia, or anti-inflammatory and adipokine-targeting strategies in individuals with high inflammatory signatures despite moderate glycemic control.

Nanobiosensors may also support adaptive interventions. Digital therapeutics that deliver personalized advice on meal timing, macronutrient composition or physical activity can be linked to biosensor feedback, closing the

loop between behavior, metabolic response and guidance. For instance, a system might identify specific foods that provoke disproportionate glycemic and inflammatory responses in a given person and recommend alternatives that minimize these excursions. Over time, this approach moves beyond static guidelines toward dynamic, data-driven lifestyle prescriptions.

On the technological front, future nanobiosensors will likely feature enhanced multiplexing, improved antifouling properties, longer operational lifetimes and more seamless integration with textiles and consumer electronics[49]. Emerging materials such as 2D heterostructures, nanozymes and advanced MOFs will expand the repertoire of detectable analytes and improve performance in challenging matrices like sweat and saliva. Multi-modal sensors that combine electrochemical, optical and mechanical signals may extract more robust information from noisy environments, while advances in microfluidics will refine sample collection and conditioning[49].

Ethical and social considerations will accompany these advances. Continuous metabolic monitoring raises questions about data ownership, privacy and consent, particularly if insurers or employers seek access to biosensor-derived risk profiles. Clear governance frameworks and technical safeguards are necessary to prevent misuse and to ensure that the benefits of early detection and personalization do not come at the cost of discrimination or loss of autonomy.

Ultimately, nanobiosensors should be viewed not as standalone solutions but as foundational components in an ecosystem of precision metabolic care. When integrated with traditional diagnostics, imaging, genomics and behavioral data, they can help clinicians and individuals understand the dynamic nature of obesity-associated dysregulation, intervene earlier and tailor strategies over time. If developed and deployed thoughtfully, nanobiosensors have the potential to reshape how obesity and its cardiometabolic complications are detected, monitored and managed across the lifespan.

CONCLUSION

Nanobiosensors are poised to play a transformative role in the early detection and continuous monitoring of obesity-associated metabolic dysregulation. By coupling nanostructured materials with selective biorecognition and flexible form factors, these devices can sensitively detect glucose, lipids, adipokines, inflammatory markers and other metabolites in non-invasive biofluids such as sweat, saliva, tears, breath and urine. Wearable and portable platforms integrated with mobile health technologies enable real-time tracking of metabolic status in everyday life, creating new opportunities for timely intervention and personalized care. Significant challenges remain in translating these technologies from laboratory prototypes to clinically validated, affordable and equitable tools, including the need for robust calibration, outcome-focused validation, regulatory clarity and user-centered design. As these hurdles are addressed, nanobiosensors are likely to become key elements in precision metabolic medicine, complementing lifestyle interventions and pharmacotherapy to improve the prevention and management of obesity and its complications.

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