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Biomarkers in Precision Medicine – Current Status and Future Developments

Chinta Supreeth[1], Shaik Khaja Nagoor Asif Ali[1*], Medidi Suma[1], Satish Kumar Vemavarapu[2]

[1]*Intern, Clinoxy Solutions Pvt., Ltd., Hyderabad, Telangana*

[2]*Founder, Clinoxy Solutions Pvt., Ltd., Hyderabad, Telangana*

Author for correspondence: **Shaik Khaja Nagoor Asif Ali***
Email: asifalibav@gmail.com

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Abstract: precision medicine has completely transformed contemporary healthcare. Biomarkers which offer quantifiable signs of physiological processes disease development and therapy response are essential to this transition. The discovery of biomarkers has been accelerated by recent developments in genomics transcriptomics proteomics metabolomics epigenetics and bioinformatics. This has allowed for more precise disease diagnosis risk prediction patient stratification targeted therapy selection and treatment monitoring across a variety of clinical conditions. This review offers a thorough summary of the state of biomarkers in precision medicine today emphasising its molecular categorisation clinical importance and growing relevance in individualised treatment. The main types of biomarkers diagnostic prognostic predictive pharmacodynamic monitoring susceptibility and safety biomarkers as well as their molecular classifications based on genomic transcriptomic proteomic metabolomic epigenetic microbiome immunological imaging and digital biomarkers are covered. The study also discusses the expanding significance of biomarkers in diabetes mellitus cardiovascular illnesses neurological disorders and autoimmune diseases as well as their clinical applications in major diseases with a focus on lung and breast cancer. Biomarkers discovery and clinical translation have been greatly improved by recent technical developments such as next generation sequencing liquid biopsy single cell sequencing multi omics integration and artificial intelligence. Despite these developments widespread clinical deployment is still constrained by issues with biomarker validation illness heterogeneity assay standardisation regulatory approval cost and ethical considerations. It is anticipated that future advancements combining multi omics technology with digital health platforms and artificial intelligence would significantly enhance illness prediction therapeutic decision making and individualised patient care. All things considered biomarkers serve as the foundation of precision medicine by connecting clinical practice with molecular research. The next wave of personalised healthcare is anticipated to be driven by ongoing advancements in biomarker discovery validation and application which will eventually improve long term patient outcomes treatment efficacy and diagnostic accuracy.

Keywords: Lipid biopsy, Precision oncology, breast cancer, lung cancer,

genomics, multi-omics, biomarkers, precision medicine, personalised medicine.

Introduction:

Precision medicine has transformed modern healthcare by replacing the traditional "one-size-fits-all" approach with individualized strategies based on each patient's unique molecular and clinical characteristics. Unlike conventional medicine which often applies standardized diagnostic and therapeutic approaches precision medicine integrates genomic epigenomic transcriptomic proteomic metabolomic environmental and lifestyle information to improve disease prevention diagnosis prognosis and treatment. This personalized approach enhances therapeutic efficacy while reducing adverse drug reactions and unnecessary interventions. Advances in molecular biology next generation sequencing (NGS) bioinformatics and artificial intelligence (AI) especially since the Human Genome Project was completed have propelled the development of precision medicine. Comprehensive molecular profiling of illnesses has been made possible by these technical advancements enabling categorisation based on underlying biological pathways rather than just clinical or histological characteristics. As a result, precision medicine has greatly enhanced the treatment of complicated illnesses including cancer heart disease diabetes neurological conditions and uncommon genetic abnormalities.

Precision medicine relies heavily on biomarkers. The FDA NIH BEST (Biomarkers Endpoints and other Tools) framework defines biomarkers as objectively detectable markers of pathogenic alterations normal biological processes or reactions to therapeutic treatments. They can be found in tissue blood urine saliva cerebrospinal fluid imaging tests and digital health platforms. They offer important information for managing illness.

There are several clinical uses for biomarkers. Predictive biomarkers identify individuals who are most likely to benefit from medications prognostic biomarkers forecast clinical outcomes and illness development and diagnostic biomarkers help discover diseases early. Pharmacodynamic biomarkers which assess biological responses to treatment monitoring biomarkers which evaluate disease activity during therapy susceptibility biomarkers which estimate disease risk and safety biomarkers which identify patients at risk of toxicity from treatment are further categories. When combined this biomarker types enhance patient care and enable tailored clinical decision making. Recent developments in multi-omics technology have significantly increased the number of biomarkers found. Genomic change transcriptomic signatures proteomic and metabolomic profiles epigenetic modifications microbiome derived indicators circulating tumour DNA (ctDNA) extracellular vesicles exosomes and digital biomarkers produced by wearable technology are examples of contemporary biomarkers. Better disease characterisation and biomarker discovery have been made possible by the combination of AI and machine learning. Oncology is the medical speciality where biomarker-guided precision therapy has been most successfully used. Actionable genetic changes that direct targeted medicines and immunotherapies have been found thanks to molecular profiling. Together with PD L1 expression and tumour mutational load biomarkers such as EGFR, ALK, ROS1, BRAF, KRAS, MET, RET, and NTRK mutations have significantly improved patient selection and treatment results in non-small cell lung cancer (NSCLC). Like this ER, PR and HER2 status are often used in the management of breast cancer and gene expression profiles circulating tumour DNA and BRCA1/2 and PIK3CA mutations continue to improve prognosis and therapeutic choices. Biomarkers are being utilised more often in conditions other than cancer such as diabetes cardiovascular disease neurological disorders autoimmune illnesses and infectious diseases. While brain fluid biomarkers and sophisticated neuroimaging enable earlier identification of Alzheimer's disease cardiac troponins and natriuretic peptides have revolutionised cardiovascular diagnosis and risk assessment. These illustrations show how biomarkers are becoming increasingly useful in a variety of treatment domains. Despite impressive advancements several obstacles prevent widespread clinical use. Due to poor repeatability diverse research populations inadequate clinical evidence and a lack of standardised validation procedures many potential biomarkers fail during validation. High implementation costs legal restrictions data standardisation ethical issues with genetic privacy and uneven access to precision medical technology are among further obstacles. It is anticipated that biomarker discovery and clinical translation will be accelerated by future developments in single cell sequencing spatial transcriptomics liquid biopsy multi omics integration artificial intelligence and digital health technologies. Early diagnosis more precise

patient classification real time therapy monitoring and more individualised therapeutic approaches will all be made possible by these developments. The primary biomarker categories molecular categorisation disease specific applications biomarker discovery technologies current clinical status difficulties and prospects for precision medicine are all covered in this study.

History of Biomarkers in precision medicine:

The idea of biomarkers has developed from basic clinical observations to complex molecular indications that direct personalised medical care. At first clinical symptoms physical examinations and standard laboratory testing were the main factors used to diagnose diseases and make treatment decisions. The basis for biomarker-based medicine was laid in the middle of the 20th century when biochemical markers including blood glucose liver enzymes and heart enzymes became useful tools for illness identification and monitoring.

A significant turning point in biomarker research occurred during the molecular biology revolution of the 1970s and 1980s. Researchers have discovered genetic and protein biomarkers linked to illness susceptibility and progression thanks to developments in DNA sequencing polymerase chain reaction (PCR) and monoclonal antibody technology. These findings changed the focus of healthcare from a generalised approach to therapy to a molecular knowledge of disease. By offering a thorough map of the human genome the Human Genome Project's completion in 2003 sped up the advancement of precision medicine. This milestone encouraged the development of pharmacogenomics which enables treatments to be customised based on a patient's genetic profile and made it easier to identify genetic variations linked to disease. Clinically useful biomarkers such KRAS mutations in colorectal cancer EGFR mutations in non-small cell lung cancer and HER2 in breast cancer were crucial in the selection of targeted therapies during this time. Rapid developments in bioinformatics artificial intelligence high throughput omics technologies and next generation sequencing (NGS) have revolutionised biomarker discovery and clinical use during the last ten years. To enhance illness prediction early diagnosis prognosis therapy selection and therapeutic monitoring modern precision medicine combines genomic transcriptomic proteomic metabolomic epigenomic and digital biomarkers. Furthermore, real time evaluation of the course of the disease and the effectiveness of treatment has been made possible by non-invasive techniques like liquid biopsy.

Biomarkers are now acknowledged as a key component of precision medicine. Biomarker guided techniques enable medical professionals to categorise patients into physiologically unique subgroups and choose treatments that maximise efficacy while minimising side effects as opposed to using a "one-size-fits-all" therapy plan. It is anticipated that ongoing developments in systems biology artificial intelligence and multi-omics integration will further broaden the function of biomarkers improving precision medicine's accuracy personalisation and accessibility across a variety of disease domains.

Types of Biomarkers:

Biomarkers are biological traits that may be measured objectively and serve as indicators of pathological diseases normal physiological processes or biological reactions to treatment treatments. By facilitating illness diagnosis prognosis patient classification therapy selection and therapeutic monitoring they play a crucial part in precision medicine. The FDA–NIH BEST (Biomarkers Endpoints and other Tools) Resource divides biomarkers into seven main groups according to how they are used in clinical settings. In clinical practice and biomarker research this standardised categorisation has emerged as the most used approach.

Diagnostic biomarkers:

To identify a particular disease subtype or to detect or confirm the existence of a disease diagnostic biomarkers are employed. These biomarkers help doctors distinguish between illnesses with similar clinical manifestations increase diagnostic precision and enable early disease diagnosis. Examples of molecular subtypes appropriate for targeted therapy include EGFR mutations in non-small cell lung cancer (NSCLC) HbA1c for diabetes mellitus HER2 expression in breast cancer and cardiac troponin for acute myocardial infarction.

Prognostic Biomarkers:

Regardless of therapy prognostic biomarkers offer information about the expected course of a disease including disease progression recurrence metastasis or overall survival. They are direct long-term patient

care and assist doctors in estimating illness outcomes. Prostate specific antigen (PSA) levels for determining the course of prostate cancer BCR ABL transcript levels in chronic myeloid leukaemia and the Ki-67 proliferation index in breast cancer are a few examples.

Predictive Biomarkers:

Patients who are more likely to react to a certain medication or suffer side effects from treatment are identified using predictive biomarkers. Because they allow for tailored treatment choices these biomarkers are essential to precision medicine. EGFR mutations ALK rearrangements PD-L1 expression in lung cancer HER2 over expression in breast cancer and BRCA1/BRCA2 mutations that predict response to PARP medicines are examples of well-known predictive biomarkers.

Monitoring Biomarkers:

Throughout the course of managing an illness monitoring biomarkers are evaluated often to assess recurrence therapy response and disease activity. They enable medical professionals to adjust treatment plans in response to alterations in the state of the illness. Examples include circulating tumour DNA (ctDNA) for identifying minimum residual illness and recurrence in cancer patients HbA1c for tracking long-term glycaemic management in diabetes viral load in HIV infection and prostate specific antigen (PSA) following prostate cancer therapy.

Pharmacodynamic Biomarkers:

After a treatment intervention pharmacodynamic biomarkers show that a biological reaction has taken place. They are commonly employed in clinical studies to assess target engagement select the best dose and monitor drug activity before to the manifestation of clinical effects. Examples include changes in blood glucose following insulin delivery a decrease in BCR ABL transcript during tyrosine kinase inhibitor therapy and a decrease in inflammatory cytokines after anti-inflammatory medication.

Safety Biomarkers:

Safety biomarkers determine or forecast the likelihood of drug induced toxicity or unfavourable treatment related outcomes. By enabling early diagnosis of organ damage or treatment related problems these biomarkers enhance patient safety. Examples include cardiac troponins for cardiotoxicity linked to specific anticancer treatments serum creatinine for kidney function and aspartate aminotransferase (AST) and alanine aminotransferase (ALT) for liver damage.

Susceptibility Biomarkers:

Risk biomarkers also known as susceptibility biomarkers identify people who are more likely to acquire a disease before clinical symptoms manifest. They encourage early screening illness prevention and individualised risk assessment. Examples include the APOE ε4 allele for Alzheimer's disease risk BRCA1/BRCA2 mutations linked to inherited breast and ovarian cancer and HLA B*57:01 which predicts hypersensitivity responses to abacavir treatment.

Biomarkers' Disease-specific Uses in Precision Medicine:

In a variety of clinical specialities biomarkers have revolutionised illness diagnosis prognosis therapy selection and treatment monitoring. Instead of depending just on clinical symptoms or histological results its incorporation into precision medicine has allowed doctors to categorise illnesses based on their molecular features. Oncology has had the most effect of all therapeutic categories but metabolic cardiovascular neurological and autoimmune disorders are also seeing an increase in the use of biomarker guided therapies.

Breast cancer:

One of the greatest instances of precision medicine based on biomarkers is breast cancer. For molecular categorisation and therapy selection routine evaluation of the human epidermal growth factor receptor 2 (HER2) progesterone receptor (PR) and oestrogen receptor (ER) has become standard practice. While HER2 positive tumours respond to HER2 targeted treatments like trastuzumab patients with ER and PR

positive tumours benefit from endocrine therapy. Furthermore, BRCA1 and BRCA2 mutations predict responsiveness to PARP medicines and identify those with inherited breast cancer. Prognosis prediction recurrence risk assessment and therapy monitoring are being improved by emerging biomarkers such as PIK3CA mutations circulating tumour DNA (ctDNA) circulating tumour cells (CTCs) and multigene expression tests.

Lung Cancer:

The discovery of several useful molecular biomarkers has made lung cancer a model illness for precision oncology. Targeted treatment selection for non-small cell lung cancer (NSCLC) is guided by biomarkers including EGFR, ALK, ROS1, KRAS, BRAF, MET and RET. Additionally tumour mutational burden (TMB) and PD-L1 expression help determine which patients are most likely to benefit from immune checkpoint medications. The necessity for recurrent tissue samples has decreased because to recent developments in liquid biopsy employing circulating tumour DNA which allow for non-invasive mutation diagnosis and therapy monitoring.

Colorectal Cancer:

Using molecular biomarker testing precision medicine has greatly enhanced the treatment of colorectal cancer. While BRAF mutations are linked to a poor prognosis and specific treatment choices mutations in KRAS and NRAS indicate resistance to anti-EGFR monoclonal antibodies. Mismatch repair deficiency (dMMR) and microsatellite instability (MSI) are frequently assessed in clinical practice as prognostic biomarkers for immunotherapy. These indicators enhance patient outcomes and allow for customised treatment plans.

Prostate Cancer:

Prostate specific antigen (PSA) continues to be the most popular biomarker for prostate cancer monitoring and diagnosis. However, by identifying individuals who could benefit from PARP inhibitors genetic biomarkers including BRCA2 ATM and other DNA repair gene abnormalities have increased therapeutic choices. Additionally, prognosis evaluation and individualised treatment plans are supported by genomic testing.

Diabetes Mellitus:

Precision medicine techniques are becoming beneficial for diabetes mellitus a complex metabolic condition. For diagnosis illness categorisation and therapy selection biomarkers including HbA1c fasting plasma glucose C-peptide insulin autoantibodies and genetic variations are often employed. In monogenic diabetes precision medicine is very helpful since genetic testing may directly direct treatment. It is anticipated that new multi omics biomarkers would enhance the prediction of type 2 diabetes complications disease progression and personalised medication response.

Cardiovascular Diseases: Validated biomarkers have a major role in the diagnosis and prognosis of cardiovascular disease. While B-type natriuretic peptide (BNP) and N-terminal pro BNP (NT-proBNP) are frequently utilised for the diagnosis and prognosis of heart failure cardiac troponins are thought to be the gold standard for identifying acute myocardial infarction. High sensitivity C-reactive protein (hs-CRP) lipoprotein (a) and genetic risk markers are examples of additional biomarkers that help in cardiovascular risk assessment and individualised treatment.

Neurological Disorders:

The diagnosis of neurodegenerative illnesses is becoming more accurate because to biomarkers. Cerebrospinal fluid indicators for Alzheimer's disease such as total tau phosphorylated tau and amyloid-β42 enable early detection prior to substantial cognitive impairment. Neuro imaging methods and blood-based indicators are becoming less intrusive options. Similar biomarker approaches are being researched for amyotrophic lateral sclerosis multiple sclerosis and Parkinson's disease.

Autoimmune and Inflammatory Disease:

Using biomarkers that show immune activity and disease progression precision medicine is increasingly being used to treat autoimmune diseases. Anti-double stranded DNA (anti-dsDNA) antibodies in systemic lupus erythematosus and anti-cyclic citrullinated peptide (anti-CCP) antibodies in rheumatoid arthritis are examples of autoantibodies that aid in diagnosis and disease monitoring. Additionally, being studied as predictive biomarkers for biological treatments are cytokines chemokines and immune cell profiling.

Biomarkers Technologies:

Genomic and Molecular Technologies:

Next Generation sequency (NGS): Because next-generation sequencing (NGS) makes it possible to quickly sequence millions of DNA fragments at once it has completely changed precision medicine. When compared to conventional Sanger sequencing NGS offers more thorough genomic analysis increased sensitivity and better throughput. Targeted gene panels whole-genome sequencing (WGS) whole-exome sequencing (WES) and RNA sequencing (RNA-seq) are all common applications of NGS. Actionable mutations including EGFR, ALK, KRAS, BRCA1/2 and PIK3CA are found by NGS in cancer allowing for more individualised therapy choices. Additionally, it is crucial for the identification of uncommon genetic illnesses pharmacogenomic variations and hereditary diseases.

Liquid Biopsy:

By examining tumour derived elements found in blood and other bodily fluids liquid biopsy has become a less intrusive option to tissue biopsy. Exosomes extracellular vesicles circulating tumour DNA (ctDNA) circulating tumour cells (CTCs) and cell-free DNA (cfDNA) are its main targets. Early cancer detection resistance mutation discovery therapy monitoring and minimum residual illness detection are all made possible by liquid biopsies. Liquid biopsy allows for the continuous collection of samples which facilitates the real-time evaluation of tumour progression throughout treatment.

Proteomic and Protein Technologies:

Proteomic Technologies: Proteomic analysis looks at the expression quantity structure and post-translational changes of proteins. The most often used methods include protein microarrays Western blotting enzyme linked immunosorbent assay (ELISA) and mass spectrometry (MS). Clinical laboratories frequently analyse protein biomarkers such HER2 cardiac troponins prostate specific antigen (PSA) and C-reactive protein (CRP). By making high resolution protein profiling possible developments in quantitative proteomics and single cell proteomics have further enhanced biomarker identification.

Metabolomic Technologies: Small-molecule metabolites that represent physiological conditions and cellular metabolism are assessed by metabolomics. The main analytical platforms are nuclear magnetic resonance (NMR) spectroscopy gas chromatography mass spectrometry (GC-MS) and liquid chromatography mass spectrometry (LC-MS). The discovery of metabolic biomarkers linked to diabetes cancer heart disease and neurological illnesses has been made easier by these technologies. Early illness identification and therapy monitoring are further benefits of metabolomic profiling.

Current Status in Precision medicine:

Precision medicine now relies heavily on biomarkers which allow for individualised approaches to illness diagnosis prognosis therapy selection and therapeutic monitoring. Genomic transcriptomics proteomics metabolomics and bioinformatics developments have sped up the search for biomarkers enabling medical professionals to customise treatments based on a patient's molecular profile. Cardiovascular metabolic neurological autoimmune and viral disorders are among the rapidly developing clinical applications of biomarker guided therapy while cancer continues to be the most advanced area.

Clinical implementation of Biomarkers:

In clinical practice biomarkers are increasingly often employed to help early diagnosis illness categorisation prognosis therapy response prediction and disease progression monitoring. Clinical guidelines in oncology suggest biomarker testing for several malignancies. Examples include EGFR, ALK

and ROS1 mutation analysis for targeted treatment of non-small cell lung cancer (NSCLC) KRAS mutation testing for colorectal cancer PD-L1 expression and tumour mutational burden (TMB) to direct immunotherapy and HER2 testing for trastuzumab therapy in breast cancer.

Companion Diagnostics:

Laboratory tests known as companion diagnostics (CDx) are used to determine which patients are most likely to benefit from targeted treatments. These tests enhance the effectiveness of treatment lessen needless toxicity and facilitate individualised therapeutic choices. Clinically proven examples are BRCA1/2 testing for PARP inhibitor treatment EGFR mutation analysis for tyrosine kinase inhibitors and HER2 testing for trastuzumab. The increasing incorporation of biomarkers into standard clinical practice is reflected in the expanding number of authorised companion diagnostics.

Precision oncology:

Precision medicine driven by biomarkers is most advanced in the field of oncology. Targeted therapy can be guided by the detection of actionable genetic changes made possible by molecular profiling. For some cancer patients biomarkers including EGFR, ALK, BRAF, ROS1, RET, MET and NTRK have greatly improved therapy results. Furthermore, immunotherapy biomarkers such as tumour mutational burden (TMB) microsatellite instability (MSI) and PD-L1 have improved patient selection for immune checkpoint inhibitors. Precision oncology has been further reinforced by the broad use of next generation sequencing (NGS).

Biomarkers Beyond Oncology:

Biomarkers are being used in therapeutic settings outside of cancer. HbA1c, C-peptide and genetic markers help in the diagnosis and customised therapy of diabetes mellitus. Cardiovascular medicine uses cardiac troponins BNP and NT-proBNP to diagnose heart failure and myocardial infarction. Cerebrospinal fluid biomarkers in neurology including total tau phosphorylated tau and amyloid-β42 aid in the early detection of Alzheimer's disease. Using autoantibodies cytokines and immune cell profiling biomarker guided treatment for autoimmune illnesses is also beneficial.

Multiple omics and Artificial Intelligence:

Biomarker development is accelerated and a thorough knowledge of disease processes is provided by multi-omics techniques that integrate genomic transcriptomic proteomic metabolomic and epigenomic data. By evaluating complicated datasets finding new biomarker signatures forecasting treatment response and assisting with clinical decision-making artificial intelligence (AI) and machine learning further improve precision medicine. In contemporary healthcare AI-driven radiomics digital pathology and computational biomarker discovery are becoming more crucial instruments.

Regulatory progress and Clinical Translation:

Regulatory organisations like the European Medicines Agency (EMA) and the Food and Drug Administration (FDA) in the United States have set up frameworks for companion diagnostics and biomarker certification. Standardised biomarker nomenclature is made possible via the FDA–NIH BEST (Biomarkers Endpoints and other Tools) Resource which promotes uniform clinical use and regulatory assessment. Widespread application is nevertheless hampered by issues with biomarker validation assay standardisation cost accessibility and reimbursement despite tremendous advancements. For precision medicine to be widely adopted it will be crucial to address these obstacles through cooperation between researchers' physicians regulatory bodies and business.

Future Developments:

Precision medicine will be propelled forward by ongoing developments in digital healthcare computational biology and molecular technology. By merging genomic transcriptomic proteomic metabolomic and epigenetic data to create thorough molecular profiles for each patient multi omics integration is anticipated to become a standard part of illness diagnosis. By spotting intricate molecular patterns that traditional statistical techniques are unable to discern artificial intelligence and machine learning will become

increasingly crucial in the search for biomarkers. Predictive analytics radiomics digital pathology and AI-assisted diagnostic tools are anticipated to enhance therapeutic decision making and illness categorisation. Although liquid biopsy technologies offer fewer invasive ways to identify extracellular vesicles circulating tumour cells (CTCs) and circulating tumour DNA (ctDNA) they will continue to grow. These methods show a great deal of promise for minimal residual illness diagnosis therapy monitoring and early cancer detection.

Another new field in precision medicine is digital biomarkers produced by wearable technology and remote monitoring systems. Early illness identification and individualised disease management may be made possible by ongoing monitoring of physiological indicators including heart rate blood glucose physical activity and sleep patterns. By identifying those at higher risk for disease before clinical signs appear the incorporation of precision medicine into standard healthcare will also help precision prevention. This proactive strategy may lessen the burden of sickness and enhance long-term health results.

Future Research Directions: Enhancing analytical validity clinical validity and clinical usefulness through extensive multicentre trials involving a variety of populations should be the main goals of future biomarker research. To guarantee that biomarkers maintain their dependability in various healthcare contexts robust validation is crucial.

To find new biomarker signatures and enhance the prediction of disease progression and treatment response more research should be done on the integration of artificial intelligence with multi omics datasets. Similarly, it is anticipated that spatial transcriptomics and single cell sequencing will offer more profound understandings of cellular heterogeneity and disease causes. To provide standardised procedures for biomarker discovery validation sample collection data analysis and clinical reporting more study is needed. The pharmaceutical sector academic institutions healthcare organisations and regulatory bodies will work together internationally to expedite the translation of biomarkers into clinical practice. Future research should also investigate pharmacogenomics precision public health strategies digital biomarkers and biomarkers derived from microbiomes. The therapeutic effect of precision medicine will be further expanded by extending biomarker research beyond cancer to include cardiovascular illnesses diabetes neurological disorders infectious diseases and uncommon diseases.

Conclusion:

Although they allow for customised diagnosis prognosis therapy selection and treatment monitoring biomarkers have emerged as the cornerstone of precision medicine. Technological developments in the fields of genomes transcriptomics proteomics metabolomics epigenetics and artificial intelligence have revolutionised the search for biomarkers and greatly enhanced our comprehension of the biology of illness. The increasing therapeutic utility of biomarker guided precision medicine is demonstrated by its effective application in cases of breast cancer lung cancer colorectal cancer diabetes mellitus cardiovascular illnesses and neurological disorders. Next generation sequencing liquid biopsy single cell sequencing digital biomarkers and multi omics integration are examples of emerging technologies that are expanding the field of personalised healthcare. Despite tremendous advancements there are still significant obstacles to overcome such as biomarker validation illness heterogeneity standardisation regulatory approval ethical issues and financial limitations. For wider clinical deployment addressing these constraints through interdisciplinary cooperation and global research projects will be crucial. Future developments in systems medicine computational biology and artificial intelligence are anticipated to speed up the search for biomarkers and smooth the shift from reactive illness management to predictive preventative and individualised healthcare. Precision medicine will be strengthened and patient outcomes will be improved globally with continued investment in biomarker research and clinical translation.

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