Therapeutics, Pharmacology and Clinical Toxicology

Review

Ther Pharmacol Clin Toxicol
Volume: 24, Issue: 1, January–March 2026

Received: 20 January 2026
Accepted: 10 February 2026

Education for personalized medicine: theoretical landmarks and interdisciplinary challenges in the genomics era

Georgiana-Ionela **Gotcu**[1]*, Constantin **Roman**[1], Camelia **Dascalu**[1], Gabriela-Dumitrita **Stanciu**[1], Bogdan-Ionel **Tamba**[1]

[1] Prof. Ostin C. Mungiu Advanced Research and Development Center for Experimental Medicine – CEMEX, Grigore T. Popa University of Medicine and Pharmacy, Iasi, Romania

*** Correspondence to:** Georgiana-Ionela Gotcu, Prof. Ostin C. Mungiu Advanced Research and Development Center for Experimental Medicine – CEMEX, Grigore T. Popa University of Medicine and Pharmacy, 16 Universitatii Str., 700115, Iasi, Romania. E-mail: georgiana.gotcu@umfiasi.ro

Abstract

Personalized medicine (PM) emerges from deep historical and philosophical roots but is being transformed by advances in genomics, multi-omics, bioinformatics and systems medicine. However, the successful clinical implementation of PM depends critically on education — a workforce equipped not only with molecular and computational skills, but with ethical, social and collaborative competencies. This review synthesizes theoretical landmarks in the development of personalized medicine, explores current educational needs and identifies interdisciplinary challenges. Finally, it proposes a paradigm for integrating theory, technology and education to support a genomics-ready health workforce.

Keywords: personalized medicine, precision medicine, genomics education, systems medicine, bioinformatics, interdisciplinary training, medical curriculum

Introduction

The accelerating transition toward personalized medicine (PM) and precision medicine represents one of the most significant paradigm shifts in contemporary healthcare. While the aspiration to tailor diagnosis and treatment to the individual is not new—its roots traceable to Hippocratic thought, Galenic constitutional medicine, and later Paracelsian theories of environmental and chemical imbalance, today's genomics era has transformed this aspiration into an actionable scientific and clinical framework [1, 2]. Personalized medicine, as conceptualized in modern biomedical discourse, is profoundly shaped by advances in molecular biology, genetic sequencing, proteomics, metabolomics, bioinformatics and systems science. These developments have necessitated new definitions, terminologies and methodological approaches that signal a transition from traditional medical models to data-intensive, predictive, participatory and integrative forms of care.

A first theoretical challenge lies in the conceptual clarification of what *personalized medicine* entails. As several analyses demonstrate, the field encompasses multiple overlapping terms: *precision medicine*, *individualized medicine*, *stratified medicine*, *P4 medicine and personalized healthcare*, each reflecting a different emphasis on molecular profiling, population-level stratification, patient participation or holistic context [3, 4]. Systematic reviews reveal that, despite heterogeneous uses, a common thread across definitions is the aim to improve patient stratification and optimize

therapeutic timing using biomarker – informed insights derived from genetics, proteomics, metabolomics and molecular disease pathways [5]. These theoretical formulations underscore a movement away from a one-size-fits-all model toward a biologically nuanced understanding of disease variation and individual response. The historical progression from pharmacogenetics of the 1950s, through the landmark demonstration of HER2-targeted therapy with trastuzumab, to multi-omics–based systems medicine exemplifies this evolution and clarifies the foundational scientific logic behind personalization [6, 7].

However, as conceptual sophistication has grown, the practical implementation of personalized medicine has revealed a substantial gap between scientific capability and workforce readiness. Numerous studies highlight inadequate education and training as one of the most persistent barriers to integrating genomics into routine clinical practice. As early as 2004, Frueh and Gurwitz [8] identified the lack of pharmacogenomics education among clinicians and the public as a critical bottleneck to translation. Subsequent studies confirm that health professionals frequently lack foundational genomic literacy, confidence in interpreting genetic tests and familiarity with emerging technologies, limitations that impede adoption even when tools are clinically available [9–11]. In response, competency frameworks have begun to articulate the skills needed for personalized precision medicine, spanning determinants of health, biomedical informatics, practical applications, participatory models of care and bioethics [12]. These frameworks emphasize not only knowledge acquisition but also attitudes, communication abilities and interprofessional collaboration across clinical, laboratory, research, digital health and managerial domains.

Educational interventions to address these gaps are inherently multidisciplinary. Specialized curricula have been developed for dermatology trainees [13], nursing and healthcare students [14] and broader interprofessional audiences, integrating reading assignments, case-based learning, laboratory rotations, experiential genome testing and assessments meant to foster applied learning. The underlying premise is that genomic medicine education must be longitudinal, beginning in undergraduate medical and health sciences programs, reinforced during residency and specialty training and sustained through continuing education. Yet even these structured initiatives confront systemic obstacles such as crowded curricula, lack of trained faculty, and institutional hesitancy to adopt genomics-driven approaches [10]. Such challenges suggest that educational reform must be systemic, requiring curricular integration not only of scientific content but also of ethical, legal, social and policy considerations. Indeed, the genomics era introduces complex interdisciplinary challenges that extend beyond the clinical domain. The volume and diversity of omics data require advanced computational methods, robust translational bioinformatics infrastructures and decision-support tools seamlessly integrated into electronic health records [15]. Data integration obstacles, including lack of standardization, interoperability issues, privacy concerns and the need for population-level validation, demand a workforce comfortable working alongside bioinformaticians, computer scientists, engineers and statisticians [16, 17]. Ethical, legal and social implications (ELSI) also multiply as genomic information becomes increasingly incorporated into healthcare. Privacy, discrimination, informed consent, biobanking governance, return-of-results protocols and potential exacerbation of health disparities all require new forms of expertise and ethical literacy among healthcare providers [18, 19]. Educating professionals to navigate these dimensions is essential to ensuring not only competent practice but also socially responsible deployment of genomic technologies.

Moreover, personalized medicine's theoretical evolution challenges educators to rethink the epistemological foundations of medical training. Philosophical analyses emphasize individuality as a multidimensional construct shaped by biology, psychology, social context, and personal history [20]. Contemporary frameworks such as systems medicine and the historical process view of disease highlight the need to understand individuals within dynamic networks of biological pathways, environmental exposures, lifestyle patterns, and sociocultural determinants [21, 22]. Preparing future practitioners for this conceptual breadth requires teaching that integrates molecular mechanisms with broader contextual and relational dimensions of health. It also necessitates cultivating the ability to work in multidisciplinary teams that bring together clinicians, engineers, data scientists, ethicists, economists, and policymakers, who are essential for managing the complex infrastructures and decision-making processes of personalized medicine [23, 24]. Against this backdrop, education becomes not simply a component of personalized medicine but a prerequisite for its very existence. As multiple authors argue, personalized medicine cannot fulfil its promise without a health workforce capable of interpreting genomic information, communicating risks and benefits, navigating ELSI issues, engaging with digital technologies, and participating in research and policy processes that shape implementation [25, 26]. This workforce must be prepared not only to understand genetic variation but also to interpret proteomic and metabolomic profiles, integrate multi-omics findings, evaluate clinical utility and appreciate the uncertainties inherent

in an evolving evidence base [27]. Thus, the transformation required in educational systems is both deep and wide: it must reach across disciplinary boundaries, across the entire continuum of professional training, and across the institutional structures that govern curriculum design and clinical practice.

In this context, the present review, "Education for Personalized Medicine: Theoretical Landmarks and Interdisciplinary Challenges in the Genomics Era", examines the convergence of these conceptual, technological, ethical, and organizational developments. By synthesizing historical trajectories, theoretical debates, evidence on training needs, and documented implementation challenges, the review aims to illuminate how educational innovation can bridge the gap between scientific potential and clinical reality. Ultimately, achieving the promise of personalized medicine will depend not solely on the sophistication of genomic technologies, but on the readiness of healthcare professionals – and the educational systems that shape them – to operate confidently and responsibly within this new paradigm.

Theoretical landmarks of personalized medicine

The intellectual foundations of personalized medicine (PM) span millennia, reflecting a long-standing effort in medical thought to reconcile general biological principles with the uniqueness of individual patients. While contemporary genomics has transformed the scale and precision of personalization, historical, conceptual and philosophical developments reveal that individualized care has always occupied a central place in the evolution of medical reasoning.

Historical roots of individualized care

The origins of personalized medicine are often traced to Hippocratic medicine, which introduced a rational, observational approach grounded in the belief that disease arises from natural, bodily processes rather than supernatural causes. According to Abrahams and Silver [1], Hippocrates established a foundational notion of "personalization" by emphasizing the need for physicians to consider constitution, environment, lifestyle and seasonality when diagnosing and treating illness. This early form of individualized care was systematized in the theory of the four humors: sanguis, phlegm, choler and melancholia, which, despite its pre-scientific framework, represented one of the first structured attempts to tailor therapies to individual physiological profiles.

By the Renaissance, the Paracelsian view further modified the concept of individualization. Paracelsus argued that disease resulted from specific imbalances in bodily minerals caused by environmental exposures and that chemicals themselves constituted both "the poison and the cure". This focus on unique, quantifiable alterations in internal chemistry anticipated later molecular understandings of disease and set conceptual groundwork for a mechanistic view of individuality.

In the early 20th century, constitutional medicine, as described by Bondio and Spöring [2], advanced the idea that disease susceptibility and therapeutic response depended on stable biological "constitutions". Theodor Brugsch's *Personallehre* extended these ideas by formalizing the study of personal biological variability, representing an important transition from classical holistic models to proto-biomedical approaches to personalization.

The mid-20th century marks a decisive theoretical landmark with the emergence of pharmacogenetics, pioneered by Friedrich Vogel, Arno Motulsky and Werner Kalow. Their work established that interindividual variability in drug metabolism is rooted in genetic variants, differentiating individuals into slow and rapid metabolizers. This principle provided the first empirical demonstration that genetic makeup could systematically influence therapeutic outcomes. As Gamma [6] notes, pharmacogenetics is widely considered the historical origin of modern personalized medicine, offering the first reproducible, molecularly grounded mechanism for stratifying patients.

The next significant milestone came with the development of trastuzumab (Herceptin) for HER2-positive breast cancer. By demonstrating that a molecular biomarker could reliably identify patients who would benefit from a specific therapy, this case provided what Gamma [6] describes as a "proof of principle" for personalized treatment. The trastuzumab example helped expand the vision of PM beyond pharmacogenetic metabolism pathways to include targeted therapies based on molecular disease subtypes. Collectively, these landmarks reveal an evolutionary arc: from observational individualization to constitution-based models, from genetic determinants of metabolism to biomarker driven targeted therapies. This conceptual trajectory sets the stage for the data-rich, multi-omics–driven personalization that characterizes contemporary precision medicine.

Modern conceptual frameworks and terminological differentiation

The rise of genomics, multi-omics profiling and computational biology has led to an explosion of terms: personalized medicine, precision medicine, stratified medicine, individualized medicine, P4 medicine and personalized healthcare, each reflecting different emphases in theory and practice.

Pokorska-Bocci *et al.* [3] analyze six such key terms, showing that debates over nomenclature reflect deeper divergences in how researchers conceptualize the goals, scope, and epistemological commitments of emerging biomedical models.

Precision medicine, popularized through the U.S. Precision Medicine Initiative, stresses the use of molecular and genetic data to improve diagnostic accuracy and tailor treatments. It is often distinguished from personalized medicine, which some critics worry implies a degree of individual tailoring that current science cannot fully deliver. Stratified medicine, by contrast, highlights grouping patients into subpopulations based on shared biomarkers, a concept grounded in statistical reasoning rather than individual uniqueness. P4 medicine, predictive, preventive, personalized and participatory, introduced by systems biologists, expands the model by emphasizing patient engagement and systems-level analysis.

A systematic literature review by Schleidgen *et al.* [5] offers one of the most comprehensive attempts to clarify these conceptual boundaries. Their precise definition states that personalized medicine aims to "improve stratification and timing of health care" by using biological information and biomarkers at the level of molecular disease pathways, genetics, proteomics and metabolomics. Importantly, their analysis revealed that despite perceived novelty, the core scientific logic of PM lies in refining patient stratification, not necessarily in creating bespoke therapies for each individual. This clarification has significant implications for education: it signals that training should focus on the interpretation of biomarkers, molecular pathways, and population-level variability rather than on an unrealistic notion of a single therapy per patient.

Contemporary frameworks also incorporate insights from systems medicine, a model supported by Hampel *et al.* [21], which conceptualizes disease as a network phenomenon arising from dynamic interactions across biological scales. Their precision medicine architecture for neurology and psychiatry integrates multimodal biomarkers, systems theory, digital health technologies and data science. This multidimensional structure underscores that modern personalization depends on the ability to synthesize heterogeneous data streams and generate clinically meaningful insights, a capacity that requires new forms of interdisciplinary literacy.

Philosophical and ethical perspectives on individuality in medicine

Beyond scientific and terminological developments, personalized medicine is grounded in enduring philosophical debates about individuality, human variation and the nature of person-centered care. Igoumenidis and colleagues [20] trace these foundations through Renaissance, Enlightenment and 20th-century philosophical traditions. Thinkers like John Locke, who emphasized individual rights and autonomy, and Thomas Hobbes, who rejected universally defined human goods, contributed to a worldview in which individuality became central to ethical and political thought. In the 20th century, existentialist movements further emphasized personal responsibility and the subjective experience of illness, ideas that resonate with contemporary movements toward patient-centered and participatory models of healthcare.

More recent theoretical proposals, such as those presented by Beneduce and Bertolaso [22], argue that disease should be understood as a historical process, shaped by genealogical, epigenetic, and contextual influences. They propose that historicity, contextuality, and relationality are essential theoretical categories for a future-oriented personalized medicine. This view challenges purely reductionist models by asserting that individuals cannot be fully understood through genomic or molecular data alone. Instead, educational approaches must acknowledge the interplay of biological, environmental, social and cultural determinants of health, dimensions vital to the ethical practice of PM.

Finally, the debates analysed by Pokorska-Bocci *et al.* [3] about whether genomics constitutes a true paradigm shift or a refinement of existing biomedical methods highlights an important philosophical tension. If personalized medicine represents a new epistemic paradigm, educators must prepare professionals for fundamentally new ways of reasoning, integrating probabilistic modeling, big data interpretation and systems-level thinking. If it is instead an extension of traditional scientific practice, then the emphasis may lie in methodological upskilling rather than conceptual reinvention. Regardless, the theoretical discourse suggests that personalized medicine requires a hybrid approach to education, both a deepening of molecular and computational competencies and a renewed engagement with ethical, relational and contextual dimensions of care.

Synthesis: implications of theoretical landmarks for education

Taken together, the historical, conceptual, and philosophical landmarks of personalized medicine reveal a field built on both continuity and disruption. From Hippocratic individuality to pharmacogenetics and systems biology, PM reflects a long-standing commitment to understanding and treating patients as biologically and contextually unique. At the same time, the genomics era introduces unprecedented complexity that demands

new competencies in data interpretation, ethical reasoning, systems thinking and interdisciplinary collaboration.

Educational programs must therefore address not only the molecular foundations of personalized medicine but also its conceptual pluralism, philosophical underpinnings and evolving epistemic frameworks. Only by integrating these theoretical insights into biomedical curricula can educators prepare a workforce capable of meeting the scientific and ethical demands of personalized medicine in the 21st century.

Educational needs in the genomics era

The rapid expansion of genomic science, multi-omics technologies and data-driven approaches has outpaced the capacity of current educational systems to prepare healthcare professionals for the realities of personalized medicine (PM). Across clinical, laboratory, research, public health and management domains, the literature consistently identifies significant gaps in genomic literacy, interpretive competency, ethical preparedness and interdisciplinary collaboration. These gaps constitute a central barrier to effective PM implementation and highlight the need for a systematic, comprehensive reconfiguration of biomedical education. This section synthesizes the major educational needs identified in contemporary scholarship, focusing on knowledge and skill deficits, competency frameworks, existing curricular innovations, and structural barriers to educational reform.

Gaps in foundational knowledge and skills among healthcare providers

Despite the proliferation of genomic technologies and molecular diagnostics, many healthcare professionals remain insufficiently prepared to integrate genomic data into clinical practice. Studies across two decades reveal persistent deficits in foundational genomic literacy, interpretation of genetic tests and understanding of molecular mechanisms relevant to personalized therapies.

Early warnings by Frueh and Gurwitz [8] emphasized that a major bottleneck in the implementation of pharmacogenomics and by extension, personalized medicine, stemmed from the inadequate education of clinicians and the wider community. This early critique remains relevant. As Squassina *et al.* [9] later demonstrated, the low educational level of healthcare providers directly influences the efficacy of PM implementation, limiting clinicians' comfort with genomic data and their ability to make informed therapeutic decisions. McCarthy [11] similarly reported that the lack of knowledge about genomics among physicians, nurses, pharmacists and other primary healthcare providers constitutes a critical barrier. Providers frequently struggle with understanding test indications, interpreting results, explaining risk to patients and integrating genomic information into clinical decision, making. Crowded curricula, insufficient exposure during training, and lack of knowledgeable faculty exacerbate these deficits.

Beyond genomics itself, personalized medicine increasingly requires understanding of proteomics, metabolomics, and systems biology, as Carlberg [26] notes, expanding the scope of necessary competencies. Providers must be able not only to interpret genetic information but also to integrate it with multi-omics profiles derived from blood, urine, or tissue samples, an educational demand rarely reflected in traditional curricula.

The cumulative picture is clear: healthcare professionals lack the baseline competencies needed to operate effectively within genomics-driven healthcare systems, necessitating targeted, structured educational interventions.

Competency frameworks and training profiles

To address these gaps, recent work has focused on defining structured competencies for the PM workforce. One of the most comprehensive frameworks is presented by Martin-Sanchez *et al.* [12], who identified 58 competencies grouped into five domains: determinants of health; biomedical informatics; practical applications of personalized precision medicine; participatory health and bioethics.

This framework acknowledges that PM competency is not limited to scientific knowledge but includes patient communication, shared decision-making, data stewardship and ethical reasoning. The authors further propose six professional profiles: clinical healthcare, laboratory, digital health, community health, research and management, each requiring tailored but overlapping competencies. Importantly, the model incorporates progressive levels of training, allowing institutions to structure curricula from introductory to advanced stages. Such frameworks align with calls from professional organizations, noting that the International Society of Pharmacogenomics Education Forum has advocated for the integration of pharmacogenomics and PM into core medical education. These calls reflect widespread recognition that genomic competency is no longer optional but fundamental to modern practice.

Educational needs identified across studies include: understanding genomic variation and molecular pathways; interpreting pharmacogenomic tests; recognizing biomarkers and companion diagnostic; applying genomic information in prevention, diagnosis and treatment; evaluating clinical

utility and evidence levels; ethical, legal and social implications (ELSI) of genomic data; communicating genomic risk and uncertainty to patients; working effectively in multidisciplinary teams; using electronic health records with genomic decision support tools. These diverse competencies reflect the expanding scope of PM and underscore the need to embed genomics education across all stages of professional development.

Existing educational models and curricular innovations

A growing number of institutions have developed specialized curricula and training models to address genomic educational gaps. These initiatives illustrate the breadth of approaches possible but also highlight their fragmented and institution-specific nature.

Specialty-specific curricula

Murphy *et al.* [13] describe a multidisciplinary curriculum in molecular diagnostics and genomics for dermatology trainees, integrating assigned readings, teaching-set reviews, lectures, presentations and a one-week rotation in a clinical molecular pathology and cytogenetics laboratory. This approach provides trainees with working knowledge of companion diagnostics, somatic and germline testing and pharmacogenomics, skills increasingly relevant across medical specialties.

Interprofessional education

Katsanis *et al.* [14] developed a formal genomics curriculum for nursing students and other healthcare professionals, emphasizing clinical applications of genomics in preventing, diagnosing, and treating complex diseases. Notably, the curriculum includes optional personal *genome testing* as an experiential learning tool, enabling participants to explore ethical, legal and psychological challenges first-hand.

Medical school integration

Frueh and Gurwitz [8] highlighted early examples of pharmacogenomics integration into medical school curricula, such as the inclusion of PGx into pharmacology courses at Tel-Aviv University School of Medicine. However, they note that such integration remains limited globally.

Active and online learning modalities

McCarthy and Patrinos [11] emphasized the importance of case-based learning, online platforms and active learning strategies to teach genomic literacy during undergraduate medical education and continuing education. These methods align with the need to engage learners in dynamic, data-rich problem-solving reflective of clinical genomic practice.

Collectively, these models demonstrate promising educational strategies. Yet, they remain largely isolated examples, highlighting the need for broad, systematic curriculum transformation.

Structural barriers to educational reform

Even as educational needs and model curricula are increasingly well defined, systemic barriers hinder their widespread adoption.

Curriculum overload and faculty limitations

McCarthy [11] reports that the crowded curriculum in medical and health sciences education leaves little room for new content, making integration difficult. Additionally, many institutions lack faculty with the expertise necessary to teach genomics, bioinformatics and PMN-related content.

Limited awareness and motivation among providers

Frueh & Gurwitz [8] and Conti *et al.* [27] note that clinicians may exhibit hesitancy or apprehension toward genomics due to uncertainty about its clinical utility or concerns about interpretation. Without clear incentives or support, providers may not pursue additional training.

Ethical and legal complexity

Brothers & Rothstein [18] highlight the expanding ethical landscape associated with genomic data-privacy, discrimination, informed consent, return of results, and requiring educational programs to incorporate sophisticated ELSI content. Few existing curricula address these aspects comprehensively.

Interdisciplinary gaps

Personalized medicine inherently requires collaboration across disciplines. Haiech & Kilhoffer [23] argue that training must prepare clinicians to work with engineers, data scientists and modelers. Yet interprofessional education remains limited, with siloed medical training insufficient for the systems-level thinking PM requires.

Infrastructure and technology challenges

Overby & Tarczy-Hornoch [15] and Najafi *et al.* [28] note that genomic integration into clinical practice depends on EHR-linked decision support tools and interoperable data systems. Training must therefore include instruction in digital health technologies, yet most programs lack this infrastructure.

Synthesis: toward a comprehensive educational framework

The literature reveals an overarching consensus: effective implementation of personalized

medicine requires a fundamentally restructured educational landscape. This includes: longitudinal genomic education spanning undergraduate training through continuing professional development; integration of multi-omics literacy, not just genetics; competency-based curricula informed by validated frameworks; interdisciplinary training models that mirror real-world PM practice; ethics-centered instruction addressing privacy, equity, and patient communication; digital literacy, including comfort with bioinformatics tools and EHR decision support; experiential learning, such as laboratory rotations, case studies, and personal genomic analysis; institutional support for faculty development and curriculum redesign. These needs underscore that education is not a peripheral component but a foundational determinant of personalized medicine's success. Without a workforce equipped to interpret genomic data, engage patients and collaborate across disciplines, the promise of PM cannot be realized.

Interdisciplinary challenges in implementing personalized medicine education

Personalized medicine is not merely a scientific advancement but an interdisciplinary enterprise that requires integration across genomics, bioinformatics, clinical practice, ethics, policy, engineering, and social sciences. As such, preparing the healthcare workforce for PM involves far more than updating biomedical curricula; it necessitates confronting a constellation of challenges emerging from the complexity of genomic information, data infrastructures, ethical and legal considerations, organizational structures, and cultural dynamics among stakeholders.

Multi-omics data complexity and the computational turn in medicine

One of the defining challenges of contemporary PM education is the explosive growth and heterogeneity of biological data. Studies consistently highlight the difficulty of integrating genomic, transcriptomic, proteomic, metabolomic, imaging and clinical data into coherent clinical workflows. Molla & Bitew identify the complexity of multi-omics integration and the high cost of comprehensive data generation as central obstacles. The heterogeneous nature of omics datasets requires advanced computational tools capable of harmonizing different data types and validating their clinical relevance.

Alyass *et al.* [16] similarly argue that systems medicine's reliance on large scale data demands a workforce capable of understanding the biological underpinnings of data integration as well as the statistical and informatics methods required to interpret it. They emphasize that interpreting multi-omics data necessitates collaboration among clinicians, epidemiologists, biologists, computer scientists, statisticians and mathematicians, teams far more diverse than those traditionally involved in clinical care.

Xue *et al.* [17] expand on this challenge by detailing the difficulties inherent in genomic variant analysis. Capturing the full spectrum of genetic variation, reliably calling germline and somatic variants, and identifying previously undetected variant types all require sophisticated computational skills. These tasks surpass the traditional scope of biomedical training and call for new educational approaches that blend biological understanding with computational literacy.

Collectively, these insights underscore a fundamental interdisciplinary challenge: the convergence of biology and data science necessitates educational programs that cultivate dual fluency in molecular mechanisms and computational tools. Without this, clinicians risk misinterpreting genomic data or relying excessively on automated systems without understanding their limitations.

Bioinformatics, decision support, and electronic health record integration

Education in personalized medicine must also prepare learners to navigate the informatics infrastructures that support genomic care. Overby & Tarczy-Hornoch [15] identify major barriers to implementing genomics applications, including validating genetic-disease correlations, assessing actionability, protecting patient privacy, and incorporating decision-support systems into electronic health records (EHRs). These challenges highlight a need for providers to understand not only clinical genomics but also the principles of translational bioinformatics. Najafi *et al.* [28] offer a detailed analysis of functional and non-functional integration requirements for linking genomics data with EHRs. Functional requirements include standardized terminologies, structured data entry, uniform interpretation of genetic tests, integrated patient portals, and pharmacogenomic decision-support capabilities. Non-functional requirements encompass interoperability, ethical and legal safeguards, security, and big data computational capacity.

These informatics challenges carry direct educational implications: clinicians must learn to interpret EHR-embedded genomic decision-support tools; learners must understand the principles of data standards, interoperability, and terminology harmonization; training must address the limitations and potential biases of algorithmic tools; providers must be educated on how to manage uncertain or evolving genomic evidence.

Without training that bridges clinical reasoning and informatics, clinicians may misinterpret automated recommendations or fail to recognize when genomic data should override traditional decision rules. Thus, PM education must integrate informatics literacy as a core competency, not an optional specialization.

Ethical, legal, and social implications (elsi): a critical educational frontier

Ethical, legal and social implications represent one of the most demanding interdisciplinary domains of personalized medicine. As genomic information becomes more deeply embedded in healthcare, providers must navigate issues that extend beyond traditional biomedical ethics. Brothers & Rothstein [18] identify several consequences of the expanding volume of health information associated with PM. These include: privacy concerns related to sensitive genomic data; risk of discrimination based on genetic profiles; changes in physician–patient relationships; liability concerns regarding interpretation and disclosure of genomic results; potential exacerbation of existing health disparities.

Joly *et al.* [19] further highlight challenges around biobanking, informed consent, confidentiality, return of results, direct-to-consumer genetic testing, and the stratification of patient populations based on ethnicity. They note that ELSI issues are particularly pronounced in primary care, where providers often lack training in genomics yet remain responsible for interpreting genetic information and guiding patient decisions.

These insights demonstrate that PM education must include comprehensive training in: ethical frameworks for genomic data use; legal regulations governing privacy, discrimination, and consent; social implications of genomics, including equity and disparities; cultural competence in communicating risk; policies on return of results and secondary findings.

This ELSI literacy is essential not only for ethical practice but also for effective clinical decision-making. Without understanding the broader social and policy context, healthcare providers may inadvertently contribute to disparities, misinterpret data, or undermine patient trust.

Institutional, organizational, and infrastructure barriers to interdisciplinary practice

Effective interdisciplinary care requires structural support within healthcare systems. Yet several studies document persistent institutional obstacles that hinder interdisciplinary collaboration and thus complicate PM education.

Erskine *et al.* [24] show that complex inherited cardiac conditions require coordinated expertise across genetics, psychology, cardiology, and ethics needs poorly met by the traditional referral-based model of care. They reveal that hospital and insurance infrastructures often impede interdisciplinary collaboration, necessitating significant modifications to current models of practice.

Cinti *et al.* [25] reinforce this by emphasizing that PM requires involvement from all stakeholder groups, including healthcare professionals, researchers, patients and the public. Training programs must reflect this diversity, yet institutional norms remain oriented toward siloed professional roles.

Haiech & Kilhoffer [23] argue that PM represents a paradigm shift from reactive medicine to predictive, model-based science, requiring clinicians to work with engineers, data scientists, and other non-medical professionals. However, most medical curricula are not designed to promote cross-disciplinary collaboration, limiting students' exposure to systems thinking and team-based problem solving.

These findings highlight the need to restructure educational environments to model the interdisciplinary teamwork that PM practice demands. Without institutional support, shared teaching platforms, interprofessional courses, team-based clinical rotations, students may never acquire the collaborative competencies essential for PM.

Cultural, evidence-based, and policy-related challenges across stakeholders

Interdisciplinary challenges also arise from broader cultural, evidentiary and policy contexts. Conti *et al.* [27] note that the slow translation of genomics into clinical practice is partly due to stakeholder apprehension: many providers, patients, and payers are uncertain about the effectiveness, cost-effectiveness and evidence base of genomic tools. Limited randomized controlled trial evidence for many pharmacogenomic tests contributes to this hesitation.

Bush *et al.* [29] identify a cultural gap across stakeholders - scientists, clinicians, patients, policymakers and payers, that complicates communication and slows adoption. Geneticists and informaticians often struggle to engage bioethicists, economists, and patient communities, while policy and reimbursement frameworks lag behind scientific advances.

These cultural and institutional misalignments underscore the need for educational programs that prepare professionals to: evaluate evidence critically; communicate genomic uncertainty; collaborate with policymakers and ethicists; understand reimbursement and regulatory landscapes; engage with patient belief systems and values.

Without such training, providers risk becoming isolated from broader implementation processes and unprepared for the complex sociotechnical environment of genomic medicine.

Synthesis: interdisciplinary challenges as drivers of educational transformation

Across the literature, a consistent theme emerges: personalized medicine is fundamentally interdisciplinary, and its successful implementation depends on a workforce capable of integrating knowledge across diverse scientific, ethical, informatic and organizational domains. Educational models must therefore evolve to: embed data science, bioinformatics, and system-level reasoning; integrate ethical, legal, and social dimensions as core competencies; support interprofessional collaboration and team-based learning; prepare providers to engage with evolving policy, regulatory, and reimbursement frameworks; address cultural apprehensions and improve communication across stakeholder groups. These interdisciplinary challenges do not merely complicate educational design; they define it. Training healthcare professionals to navigate the genomics era requires a reimagining of medical education that aligns theoretical foundations, technological capabilities, and institutional realities into a coherent, future-ready framework.

Toward a new paradigm: integrating theory, technology and education

The convergence of historical insights, conceptual frameworks, multi-omics technologies, systems medicine and interdisciplinary ethics presents both an opportunity and a mandate to reimagine how education for personalized medicine (PM) is structured. As the genomics era reshapes the epistemology, methodology and organization of medical practice, educational programs must evolve from additive models, where new content is simply appended to existing curricula, to transformative models that prepare professionals for a fundamentally different paradigm of care.

Integrating theoretical foundations into clinical and educational practice

The theories that underpin personalized medicine, from Hippocratic individuality and constitutional medicine to systems biology and P4 frameworks, carry practical implications for how clinicians are trained to think, reason, and act. Modern PM practice is rooted in the conceptual shift from viewing disease as an isolated entity to understanding it as a dynamic, historically situated process shaped by interactions among molecular, environmental, and social factors. Reinforcing this conceptual foundation in training can help learners cultivate a flexible mindset capable of integrating multi-level biological information. Systems medicine, as articulated by Hampel *et al.* [21] for central nervous system disorders, offers a model for education: multimodal biomarkers, digital technologies, and data science converge to provide holistic, predictive, and mechanism-based clinical insights. Embedding this systems-thinking approach into medical education can help students navigate the inherent complexity of PM. It shifts the focus from memorizing static facts toward developing analytical frameworks for interpreting biological variability, contextual influences, and patient-specific trajectories.

Furthermore, the conceptual clarifications offered by Schleidgen *et al.*, 2013 [5] and Pokorska-Bocci *et al.*, 2014 [3] delineating personalized, precision, stratified, and P4 medicine, suggest that educational programs must teach not only *how* to use genomic tools but *why* they are used. Clarifying the goals of PM (stratification *versus* individualization, prediction *versus* participation) anchors students' understanding of how genomic evidence informs clinical care and policy. In this way, theory becomes a navigational tool rather than an abstract academic exercise.

Integrating technology: building digital, bioinformatic and multi-omics literacy

As personalized medicine becomes increasingly data – driven, technological fluency becomes a foundational competence. The integration of genomic sequencing, proteomics, metabolomics, and advanced analytics into clinical workflows demands that educational programs cultivate multi-omics literacy, bioinformatics competencies, and digital health proficiency across the healthcare workforce.

Molla & Bitew emphasize that data integration across omics layers is one of the most significant hurdles to PM implementation. Similarly, Alyass *et al.* [16] and Xue *et al.* [17] detail how interpreting genomic variants, integrating heterogeneous datasets, and managing data uncertainty require advanced computational tools and analytical skills. These competencies cannot be confined to specialists; they must be woven into general medical and health sciences education.

Informatics integration introduces further educational demands. Overby & Tarczy-Hornoch [15] highlight the necessity of embedding decision support systems within electronic health records (EHRs) to enable the clinical use of genomic data. Najafi *et al.* [28] define both functional and non-functional integration requirements for EHR–genomics integration, including standardized terminologies, uniform interpretation frameworks

and security measures. Training programs that incorporate these informatics principles – through simulation, hands-on modules, and case-based EHR exercises can equip learners to navigate emerging digital ecosystems confidently.

Moreover, digital health technologies, including mobile health tools, clinical decision support dashboards, and patient portals, must be understood as integral components of PM rather than peripheral add-ons. As Hampel *et al.* [21] suggest, these tools are part of the architecture of precision medicine and should therefore be embedded in educational design from the outset.

Integrating ethics and social context: preparing providers for complex decision-making

A new paradigm for PM education must incorporate ethical, legal and social implications (ELSI) as central features rather than optional supplements. Brothers & Rothstein [18] demonstrate that personalized medicine carries profound consequences for privacy, discrimination and health disparities, while Joly *et al.* [19] highlight the unique ethical challenges that arise in primary care contexts, including informed consent, biobanking and the return of results.

Educational programs must therefore provide: robust grounding in genomic privacy frameworks; training in non-discrimination laws and anti-stigma communication; instruction on risk communication, uncertainty, and patient-centered counselling; structured engagement with the equity implications of genomic testing; skills for navigating cultural and belief systems related to genetics.

This ELSI literacy is essential not only for ethical practice but also for effective clinical decision-making. Without understanding the broader social and policy context, healthcare providers may inadvertently contribute to disparities, misinterpret data, or undermine patient trust. Integrating ethics with scientific and informatic training reflects the core interdisciplinarity of PM.

Integrating interprofessional learning: building teams for systems medicine

Personalized medicine is inherently collaborative, requiring coordinated efforts across clinical specialties, laboratory science, bioinformatics, engineering, ethics, and policy. Haiech & Kilhoffer [23] argue that PM represents a paradigm shift toward predictive, model-driven medicine that demands multidisciplinary teamwork. Similarly, Erskine *et al.* [24] demonstrate that managing complex genetic disorders requires integrated teams, as traditional referral-based models are insufficient.

Educational systems must therefore model the collaborative structures that PM practice requires. This entails: interprofessional courses bringing together medicine, nursing, pharmacy, genetics, computer science, and data science students; joint simulation exercises using genomic cases requiring multi-expert input; clinical rotations in interdisciplinary environments such as cardiogenetics clinics; collaborative capstones integrating genomics, ethics and digital health technologies. Such approaches support the development of communication, coordination, and problem-solving skills competencies essential for functioning in the genomics era.

Integrating policy, evidence appraisal and stakeholder engagement

The broader socio-political context of personalized medicine also shapes educational needs. Conti *et al.* [27] emphasize that translational hurdles include limited evidence for clinical utility and stakeholder apprehension regarding the cost-effectiveness and value of genomic interventions. Bush *et al.* [29] identify cultural and logistical gaps across scientists, clinicians, policymakers and payers, which complicate implementation. Educating future providers requires: critical appraisal skills for genomic evidence; awareness of regulatory frameworks and reimbursement structures; understanding of stakeholder perspectives, including patient beliefs and payer priorities; familiarity with health technology assessment in genomics. Such competencies prepare clinicians not only to use genomic tools but also to participate in shaping the policies and systems that govern them.

Synthesis: toward a coherent paradigm of integrated education for personalized medicine

The literature makes clear that personalized medicine requires a fully integrated educational paradigm, one that unites: theoretical foundations from history, philosophy, and systems science; technological fluency in genomics, multi-omics, bioinformatics, and digital health; ethical and social literacy addressing privacy, equity, consent, and discrimination; interprofessional collaboration modelled on real-world PM infrastructures; policy awareness and evidence evaluation for informed decision-making. In this integrated paradigm, theory informs practice, technology operationalizes theory and education align clinicians' competencies with the complex demands of modern healthcare systems. Achieving this alignment

requires institutional commitment, interdisciplinary leadership, and sustained curricular innovation. Personalized medicine's future and its equitable implementation will depend not only on scientific advances but on the capacity of educational systems to adapt, transform, and integrate across the full spectrum of knowledge domains that shape the genomics era.

Future directions

Personalized medicine represents both a continuation of longstanding medical traditions that seek to understand the individual in context and a transformative shift driven by genomics, systems biology, digital health, and multi-omics technologies. This review has examined the theoretical foundations of personalization, the expanding educational demands in the genomics era and the interdisciplinary challenges that shape implementation. Across diverse lines of evidence, from historical analyses and conceptual frameworks to empirical studies and policy critiques, a consistent conclusion emerges: education is the critical determinant of whether personalized medicine can be responsibly and effectively integrated into healthcare systems.

The theoretical landmarks of PM, rooted in Hippocratic and Galenic traditions, constitutional medicine, pharmacogenetics and contemporary systems thinking, reveal that personalized medicine is not a wholly new enterprise but an evolving conceptual continuum. However, the technological landscape of the 21st century has transformed the scale and granularity of personalization, making genomic literacy, multi-omics interpretation, and data-driven decision-making core competencies for modern practitioners. As Schleidgen *et al.*, Pokorska-Bocci *et al.*, and Nardini *et al.* [3–5] show, the very definition of personalized or precision medicine is complex, dynamic and deeply intertwined with methodological advances and evolving epistemological commitments. These theoretical insights underscore the need for educational approaches that foster conceptual clarity and systems-level reasoning. From an educational standpoint, the literature identifies significant deficiencies that hinder PM implementation: insufficient genomic literacy, limited pharmacogenomic training, lack of bioinformatics exposure, and inadequate preparation for ethical and communication challenges [8–10]. Competency frameworks, such as those defined by Martin-Sanchez *et al.* [12], offer structured pathways to address these gaps, outlining the domains and profiles necessary for a genomics-ready workforce. Curricular innovations – ranging from specialty-specific programs [13] to interprofessional genomics courses with experiential learning [14] demonstrate promising models but remain fragmented and insufficient without broader institutional support.

Interdisciplinary challenges further complicate the educational landscape. The integration of multi-omics data, the need for advanced computational literacy, and the incorporation of bioinformatic tools into electronic health records require clinicians to collaborate with data scientists, engineers, and informaticians. Ethical, legal, and social issues such as privacy, genomic discrimination, biobanking governance, and health disparities demand training that extends beyond scientific knowledge to include policy awareness and ethical reasoning. Structural limitations within healthcare systems-referral models unsuited for genomic complexity and cultural gaps among stakeholders, underscore the need for interprofessional education and a systems-level approach to clinical implementation. Taken together, these findings indicate that the future of PM education requires a paradigm shift. Moving forward, several key directions emerge: build fully integrated, competency-based curricula spanning all stages of professional training; develop interprofessional and systems-oriented training models reflecting real-world PM practice; expand ethical, legal, and social literacy to equip providers for responsible genomic care; strengthen digital and data-science competencies necessary for multi-omics, EHR integration, and decision-support; promote institutional transformation including faculty development, infrastructure, and policy adaptation; enhance public and patient education to foster trust and informed engagement; support rigorous research on educational effectiveness to guide best practices and policy.

Conclusion

Personalized medicine is often portrayed as a scientific revolution driven by genomics. Yet the literature reviewed here makes clear that its success hinges not only on technology but on people, their knowledge, skills, ethical sensitivity, and capacity to work across disciplinary boundaries. The future of personalized medicine will depend on an educational paradigm capable of integrating theory, technology and practice into a coherent framework that prepares healthcare professionals for the complexities of genomic era medicine. In this sense, education is not simply one pillar of personalized medicine; it is the foundation upon which all other pillars: biomarkers, systems biology, digital health and data science.

Acknowledgments

Conflict of interest

The authors declare no conflict of interest.

References

1. Abrahams E SM. The history of personalized medicine. In: Gordon E KS, editor. Integrative Neuroscience and Personalized Medicine. Oxford University Press; 2011.
2. Bondio M.G., Spöring F. Personalized medicine: historical roots of a medical model. In: Boniolo G., Nathan M.J., editors. Philosophy of Molecular Medicine: Foundational Issues in Research and Practice. Taylor & Francis; 2016. p. 35–56.
3. Pokorska-Bocci A, Stewart A, Sagoo GS, Hall A, Kroese M, Burton H. 'Personalized Medicine': What'S in a Name? Per Med. 2014 Mar 23;11(2):197–210.
4. Nardini C, Osmani V, Cormio PG, Frosini A, Turrini M, Lionis C, Neumuth T, Ballensiefen W, Borgonovi E, D'Errico G. The Evolution of Personalized Healthcare and the Pivotal Role of European Regions in its Implementation. Per Med. 2021 May 7;18(3):283–94.
5. Schleidgen S, Klingler C, Bertram T, Rogowski WH, Marckmann G. What is personalized medicine: sharpening a vague term based on a systematic literature review. BMC Med Ethics. 2013 Dec 21;14(1):55.
6. Gamma A. Personalized and precision medicine. In: Solomon M, Simon JR, Kincaid H, editors. The Routledge Companion to Philosophy of Medicine. Routledge; 2016.
7. Offit K. Personalized medicine: new genomics, old lessons. Hum Genet. 2011 Jul 26;130(1):3–14.
8. Frueh FW, Gurwitz D. From Pharmacogenetics to Personalized Medicine: A vital Need for Educating Health Professionals and the Community. Pharmacogenomics. 2004 Jul 5;5(5):571–9.
9. Squassina A, Manchia M, Manolopoulos VG, Artac M, Lappa-Manakou C, Karkabouna S, Mitropoulos K, Zompo M Del, Patrinos GP. Realities and Expectations of Pharmacogenomics and Personalized Medicine: Impact of Translating Genetic Knowledge into Clinical Practice. Pharmacogenomics. 2010 Aug 12;11(8):1149–67.
10. Mullikin JC. The evolution of comparative genomics. Mol Genet Genomic Med. 2014 Sep 5;2(5):363–8.
11. McCarthy J, Patrinos GP. Educating Healthcare Providers in the Delivery of Genomic Medicine. Per Med. 2019 May 13;16(3):187–8.
12. Martin-Sanchez F, Lázaro M, López-Otín C, Andreu AL, Cigudosa JC, Garcia-Barbero M. Personalized Precision Medicine for Health Care Professionals: Development of a Competency Framework. JMIR Med Educ. 2023 Feb 7;9:e43656.
13. Murphy MJ, Shahriari N, Payette M, Mnayer L, Elaba Z. Development of a curriculum in molecular diagnostics, genomics and personalized medicine for dermatology trainees. J Cutan Pathol. 2016 Oct 22;43(10):858–65.
14. Katsanis SH, Dungan JR, Gilliss CL, Ginsburg GA. Educating future providers of personalized medicine. N C Med J. 2013;74(6):491–2.
15. Overby CL, Tarczy-Hornoch P. Personalized Medicine: Challenges and Opportunities for Translational Bioinformatics. Per Med. 2013 Jul 3;10(5):453–62.
16. Alyass A, Turcotte M, Meyre D. From big data analysis to personalized medicine for all: Challenges and opportunities. Vol. 8, BMC Medical Genomics. BioMed Central Ltd.; 2015.
17. Xue Y, Lameijer EW, Ye K, Zhang K, Chang S, Wang X, Wu J, Gao G, Zhao F, Li J, Han C, Xu S, Xiao J, Yang X, Ying X, Zhang X, Chen WH, Liu Y, Zhang Z, Huang K, Yu J. Precision Medicine: What Challenges are We Facing? Genomics Proteomics Bioinformatics. 2016 Oct 1;14(5):253–61.
18. Brothers KB, Rothstein MA. Ethical, Legal and Social Implications of Incorporating Personalized Medicine into Healthcare. Per Med. 2015 Jan 6;12(1):43–51.
19. Joly Y, Saulnier KM, Osien G, Knoppers BM. The ethical framing of personalized medicine. Curr Opin Allergy Clin Immunol. 2014 Oct;14(5):404–8.
20. Igoumenidis M, Papastavrou E, Lemonidou C. Theoretical and Philosophical Framework for Individualised Care. In: Suhonen R, Stolt M, Papastavrou E, editors. Individualized Care: Theory, Measurement, Research and Practice [Internet]. Cham: Springer International Publishing; 2019. p. 7–15. Available from: https://doi.org/10.1007/978-3-319-89899-5_2
21. Hampel H, Gao P, Cummings J, Toschi N, Thompson PM, Hu Y, Cho M, Vergallo A. The foundation and architecture of precision medicine in neurology and psychiatry. Trends Neurosci. 2023 Mar;46(3):176–98.
22. Beneduce C, Bertolaso M. Personalized Medicine in the Making: Philosophical Perspectives from Biology to Healthcare. In.
23. Haiech J, Kilhoffer MC. Personalized medicine and education: the challenge. Croat Med J. 2012 Aug;53(4):298–300.
24. Erskine KE, Griffith E, DeGroat N, Stolerman M, Silverstein LB, Hidayatallah N, Wasserman D, Paljevic E, Cohen L, Walsh CA, McDonald T, Marion RW, Dolan SM. An Interdisciplinary Approach to Personalized Medicine: Case Studies from a Cardiogenetics Clinic. Per Med. 2013 Jan 19;10(1):73–80.
25. Cinti C, Trivella MG, Joulie M, Ayoub H, Frenzel M. The Roadmap toward Personalized Medicine: Challenges and Opportunities. J Pers Med. 2024 May 21;14(6):546.
26. Carlberg C. The Need for Education in Personalized Medicine. Per Med. 2012 Mar 6;9(2):147–50.
27. Conti R, Veenstra DL, Armstrong K, Lesko LJ, Grosse SD. Personalized Medicine and Genomics: Challenges anOpportunities in Assessing Effectiveness, Cost-Effectiveness, and Future Research Priorities. Medical Decision Making. 2010 May 4;30(3):328–40.
28. Najafi A, Emami N, Samad-Soltani T. Integration of Genomics Data and Electronic Health Records Toward Personalized Medicine: A Targeted Review. Frontiers in Health Informatics. 2021 Aug 22;10(1):86.
29. Bush WS, Cooke Bailey JN, Beno MF, Crawford DC. Bridging the Gaps in Personalized Medicine Value Assessment: A Review of the Need for Outcome Metrics across Stakeholders and Scientific Disciplines. Public Health Genomics. 2019;22(1–2):16–24.