PERSONALIZED MEDICINE: A COMPARATIVE ANALYSIS OF IMPLEMENTATION AND CHALLENGES IN NORTH MACEDONIA AND EUROPEAN COUNTRIES

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Abstract

Personalized medicine represents a fundamental transformation in the health system in the prevention, diagnosis and treatment of patients based on their genetic profile. The use of genomic, pharmacogenetic and clinical data enables safer and more effective treatment. The most developed European countries have made great progress in this direction, while in some regions, including North Macedonia, the implementation of personalized medicine still remains very limited.

Our research intends to perform a comparative study on the progress of personalized medicine in some of the most developed European countries like England, France and Germany to that of North Macedonia. We conducted a literature review of the topics of interest that are genetic and pharmacogenetic testing, biomarker-based diagnostics and the introduction of genomics in healthcare systems. European countries have been gradually moving towards personalization of health, for example, through national genomic projects, a range of new technologies and clinical guidelines that are sufficiently advanced to make targeted therapies and pharmacogenetic testing a part of everyday clinical practice.

On the other hand, in North Macedonia, the project is barely taking off and is mostly confined to a few specialized healthcare and research facilities. The testing methods that can be adopted are targeted genotyping, PCR-based assays and the new next-generation sequencing techniques; however, their broader use is hampered by a lack of infrastructure, financial barriers, absence of standardized guidelines and shortage specialized staff.

Keywords: Personalized Medicine, Genetic Testing, Healthcare Implementation, Comparative Analysis, European Healthcare Systems, North Macedonia

Introduction

Personalized medicine focuses on tailoring each patient's prevention, diagnosis, and treatment based on their unique characteristics and it is one of the main changes to modern healthcare (Francis S. Collins & Harold Varmus, 2015; European Commission, n. d.). Unlike traditional medicine that simply follows established treatment protocols personalized medicine takes into account the genetic differences biomarker profiles clinical data and environmental factors to best meet patient needs and low adverse effects (Ashley, 2016; Goetz & Schork 2018). The evolution of genomics next-generation sequencing technologies and bioinformatics have greatly helped in the progress of precision medicine allowing disease classification and treatment personalization to reach unprecedented levels of precision (Eric J. Topol, 2014; International Human Genome Sequencing Consortium, 2004).

Examples of personalized medicine in the clinic include cancer treatment, cardiac care and drug therapy. In cancer treatment the use of molecular analyses has made it possible to find the mutation causing the cancer and then to produce a drug that specifically targets it; in general patient survival and response to therapy have been substantially improved with targeted drugs (National Cancer Institute, 2020; Garraway & Lander, 2013). Genetic testing in cardiology and pharmacogenetics also guides the selection of the most appropriate

therapeutic agent and the determination of the right dose so as to minimize adverse drug reactions and maximize the therapeutic outcome (Reling et al, 2019; Roden et al. 2019). Great variations in pharmacogenetics have mainly been documented for genes playing roles in drug metabolism which is one reason why pharmacogenetics have become an important aspect of individualized treatment strategies (Roden et al 2011; Noveski et al 2025; Pereira NL & Weinshilboum RM 2009; Dunnenberger et al., 2015).

Significant advances have been made in personalized medicine throughout Europe, mainly via national genomic strategies, massive biobanks, and the regular application of molecular diagnostics (European Commission, 2022; European Alliance for Personalised Medicine, 2020). The United Kingdom, France, and Germany are leading examples of the effective reuse of those technologies. In the UK, the Genomics England program, especially the 100,000 Genomes Project, has allowed the use of genomic data for regular clinical care, mainly in the fields of oncology and rare diseases (Genomics England, 2018). In France, the "France Mdecine Gnomique 2025" plan has put in place a national network for genomic sequencing and data sharing, helping precision diagnostics and personalized therapies (Auffray et al. 2016). Likewise, Germany has rolled out national programs targeting precision medicine and digital health, encouraging the use of genomic data in medical decision-making and bolstering translational research (German Federal Ministry of Health, 2020).

These European examples show that coordinated national strategies, funding of infrastructure, cross-disciplinary teamwork, and planing clinical guidelines are crucial elements in the successful launch of personalized medicine. Besides, the presence of extensive genomic databases, combining electronic health records, and enabling ongoing professional development effectively support the adoption of precision medicine in those countries.

The application of personalized medicine in North Macedonia is at nascent phase and the practice is mostly confined to a few clinical and research centers specialized in a particular area. However, some recent research has recognized a greater use of genomic and pharmacogenetic techniques in the country. pharmacogenetic studies have pointed to the direct relationship between genetic differences and treatment results, for instance, the AKR1D1*36 allelic variant has been reported as an independent factor affecting clopidogrel therapy effectiveness, which underscores the role of individualized treatment approaches in cardiovascular patients (Kapedanovska-Nestorovska et al. 2019).

On the other hand, population-level genomic analyses with whole exome sequencing have uncovered a rich pharmacogenetic allele repertoire of the local population, including clinically relevant variants and newly discovered potentially functional mutations that may impact drug response (Noveski et al. 2025). Such results support the necessity of population-specific genetic profiling for enhancing therapeutic accuracy.

Also, some great analytical frameworks for precision genomics that clinically enable variant filtering and interpreting with the aim of identifying the clinically relevant genetic info and its healthcare decision impact are discussed (Mehandziska et al. 2020). Molecular profiling programs led by genetic alterations in major driver genes in lung cancer have been uncovered, sparking the use of targeted therapies and personalized treatments among approaches (Eftimov et al. 2025).

Nonetheless, the application of personalized medicine in clinical practice in North Macedonia is still very modest. The main problems are the scarcity of advanced genomic technologies, limited infrastructure, very high costs, absence of standardized clinical guidelines, and low

training levels of healthcare professionals. These challenges will further limit the wide-scale implementation of precision medicine in the country's healthcare system.

Yet, the personalized medicine is still very promising because it can bring major benefits such as more effective treatments, less toxic side effects, the possibility of drug selection that fits patients individually, and overall safety of patients (Ashley, 2016). Nevertheless, from the angle of ethics, there are concerns about privacy of genetic information, inequalities in availability of tests, and difficulties in understanding genomic data which are primary reasons for people's resistance to genetic medicine (Geoffrey S. Ginsburg & Katherine A. Phillips, 2018).

Due to the differences in implementation among various healthcare systems, it is crucial to do a comparative study between North Macedonia and top European countries like the UK, France, and Germany to get a clear picture of current progress, pinpoint gaps, and think of ways for future development. This kind of study offers great understanding on how well-performing European models can be localized for the purpose of promoting precision medicine and enhancing patient outcome.

Aim of the study

This study is fundamentally about exploring the contribution of personal medicine to the healthcare sector and the investigation of its progress and dissemination in North Macedonia as compared to the top European countries such as the United Kingdom, France, and Germany.

The study primarily intends to evaluate the extent to which genomic and pharmacogenetic methods have been implemented in the clinical setting, for example, the employment of genetic testing, use of biomarkers for diagnosis, and therapy based on the patient's characteristics. Besides, the study attempts to unveil the utmost positive aspects of personalized medicine - like higher effectiveness of treatment and lowered risk to the patient - along with the most pressing constraints, including technical, moral, and financial difficulties. Moreover, the purpose of the present research lies in evaluating the significant problems, which slow down the introduction of personalized medicine in North Macedonia, for example, lack of proper infrastructure funds introduction of cutting-edge technology, and human resources training. By applying the comparison of these issues faced by the two countries, this study sees the European models of personalized medicine as a chance for a healthcare system improvement in North Macedonia.

On one hand, the research gives a clear picture of how personalized medicine is practiced currently and, on the other hand, presents realistic approaches in order to push precision medicine forward and yield better results from healthcare activities at the level of the national health system.

Methodology

This research was narrative comparative review aiming to analyze and compare the implementation of personalized medicine in North Macedonia and selected European countries, including UK, France, and Germany. The secondary research was done through a high degree of literature review which includes critical evaluation of scientific literature, clinical trials, and institutional reports.

Scholarly journals, international clinical guidelines, and reports by scientific organizations and health care institutions have been the main sources of data. The selection of sources was primarily based on studies that focused on the main components of personalized medicine such as genetic and pharmacogenetic testing, diagnostics based on biomarkers, and the utilization of genomic data in the clinic.

The analysis included:

1. A comparative evaluation of the level of implementation of personalized medicine between North Macedonia and selected European countries
2. An assessment of available testing methodologies, including targeted genotyping, polymerase chain reaction (PCR)-based assays, and next-generation sequencing techniques such as whole exome sequencing
3. Identification of the main advantages and limitations of personalized medicine across different healthcare systems
4. Evaluation of key challenges affecting implementation, including infrastructure, financial constraints, accessibility of testing, and availability of trained healthcare professionals

A qualitative analytical approach was used to synthesize and interpret the findings, allowing for a comprehensive understanding of current practices and future perspectives. No primary data were collected, as the study relies on the critical comparison of existing evidence.

Results and Discussion

Reviewing various studies points out a major gap in the implementation of personalized medicine between North Macedonia and highly developed European countries like the United Kingdom, France, and Germany. These countries have gradually incorporated personalized medicine into their healthcare systems through national genomic policies, large-scale sequencing programs, and the frequent use of pharmacogenetic testing (European Commission, 2022; Auffray et al. 2016). For instance, in the UK, the Genomics England project has made it possible to regularly use genomic information in clinical decisions, especially in cancer and rare diseases (Genomics England, 2018). Likewise, France has rolled out a national genomic strategy to bring sequencing technologies into medical practice, and Germany has promoted precision medicine thanks to its focus on the development of the digital health infrastructure and the funding of translational research programs (Auffray et al. 2016; European Commission, 2022).

Such changes have notably enhanced the accuracy of diagnoses and have been instrumental in the appropriate use of targeted therapies, mainly in oncology and pharmacology, which have been linked to improved clinical outcomes (Ashley, 2016; Garraway & Lander, 2013). On the other hand, North Macedonia is still at the stage where personalized medicine is being planned and is mostly found in specialized institutions and research environments.

Local studies provide evidence supporting the entry of genomic and pharmacogenetic methods in North Macedonia, although they are not yet widely used. A large-scale pharmacogenetic study based on whole exome sequencing uncovered an extensive panel of alleles, among which could be found variants with a direct impact on drug metabolism and response, as well as newly discovered potentially functional variants (Noveski et

al. 2025). Such data highlight the critical role of population-specific genomic information in the development of therapeutioc propositions.

Molecular profiling studies of lung cancer patients in North Macedonia in the field of oncology have revealed a high percentage of individuals having genetically actionable alterations in major genes such as EGFR, KRAS, and PIK3CA (Eftimov et al. 2025). These findings prove the clinical significance of genomic testing in the decision-making process of targeted therapies. Nevertheless, the daily use of these methods is still very limited mainly due to the infrastructure and financial issues.

Moreover, precision genomics can only be used efficiently if there are analytical frameworks that are properly structured. The creation of genomic data filtering workflows and interpretation, including both variant-centric and gene-centric methods, has been found to greatly enhance the identification of clinically actionable variants and their clinical application (Mehandziska et al. 2020). These kinds of frameworks are extensively used by more advanced healthcare systems in Europe, but continue to be the focus of development in North Macedonia.

Even though these are very good indicators of the potential of personalized medicine, a number of obstacles continue to prevent its widespread adoption in North Macedonia. Limiting factors are among others the lack of infrastructure, the limited availability of advanced genomic technologies, the high cost of implementation, and the absence of standardized clinical guidelines. On top of that, the inadequacy of training and expertise in genomic medicine makes the integration of this approach into regular practice even more difficult (Vogenberg et al. 2010; Ginsburg & Phillips, 2018).

The East-European countries like the UK, France, and Germany reveal that the key factors for effective implementation are national strategy alignment, continuous financial support of genomic infrastructure, inclusion of genetic testing in health care provision, and ongoing professional training (European Commission, 2022; Auffray et al. 2016). The countries serve as an example for North Macedonia in terms of personalized medicine development.

To sum up, the results show that personalized medicine has a great opportunity to enhance health outcomes, but its application in North Macedonia is still at a very initial stage when compared with more developed European countries. Building up physical capacity, increasing opportunities for genetic testing, and implementing well-defined clinical and regulatory guidelines will be the main measures for narrowing this inconsistency and for the progress of precision medicine in the area.

Conclusion

Personalized medicine is the use of genomic information and other personal data of individuals to tailor the diagnosis and treatment of a disease or condition more precisely, effectively, and with consideration of the patient's preferences and needs. In Europe, for instance, the UK, France, and Germany have developed robust systems for the implementation of personalized medicine ' precision medicine '. These countries have established national genomic strategies, invested in advanced sequencing technologies, and made genetic testing and biomarker analysis a part of routine clinical practice. Consequently, they showcase enhanced diagnostic precision, broader use of targeted therapies, and more cost-effective healthcare delivery.

On the other hand, personalized medicine ' precision medicine ' in North Macedonia faces the challenge of being at a very early stage of development. Though some advances have been made in pharmacogenetics and molecular diagnostics, their extent of implementation is still very limited and is mostly available only in specialized centers. Main obstacles are the insufficient health infrastructure, the very expensive nature of the advanced technologies, the absence of standard clinical guidelines, and the scarcity of trained healthcare professionals.
Even with these disparities, the expanding research and first clinical uses show that personalized medicine can greatly help healthcare in North Macedonia. To catch up with more developed European countries, the country will need to make strategic investments, increase genetic testing, create policies, and consider successful European models that can be adapted to their circumstances.
Finally, although differences in implementation continue, personalized medicine is a necessary move towards healthcare that is more efficient, safer, and tailored to each individual. Also, its progress will be vital for the future of medical practice throughout Europe.

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