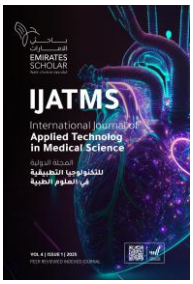

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The Role of AI in Early Diagnosis, Management, and Clinical Research of Primary Immunodeficiency Diseases: Insights from GCC Immunologists

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ABSTRACT

Primary Immunodeficiency Diseases (PIDs) are a family of approximately 450 rare disorders each with distinct diagnostic challenges because of their diverse clinical signs and the community's limited knowledge of them. Because of these challenges, patients receive their diagnoses later than optimal, tend to experience more complications, and generally receive suboptimal care. The correct and timely identification of patients with PIDs remains critical because it allows for a better prognosis as well as timely and effective management. The advancements in artificial intelligence, especially machine learning and natural language processing show potential to address current challenges in the early diagnosis of PIDs and the development of optimal management and research strategies. This study aims to investigate the perception of immunologists from GCC countries on the application of AI in the diagnosis and management of PID and in research to understand their level of awareness of AI, their perceptions of the usefulness of AI, and the major difficulties that might limit its adoption. The findings of this study can inform policy making, resource management, and strategy development for the incorporation of AI into PID care to improve patient outcomes.

1. Introduction

Primary Immunodeficiency Diseases (PIDs) are defined as more than 450 rare genetic disorders (over 450 disorders) that are characterized by the failure of the immune system (Abolhassani et al., 2020). These disorders bring about repeated infections, increase the incidence of autoimmune diseases and raise the risk of cancer (El-Sayed & Radwan, 2020). This delay in recognition leads to treatment postponements and less-than-optimal patient outcomes (Balogh et al., 2015). This is because correct and early diagnosis is critical to start the right treatment in a time manner to enhance the patient's survival and also to use the health care resources effectively (Balogh et al., 2015).

Artificial Intelligence (AI) is now considered as a revolutionary advancement in healthcare that is addressing some of the traditional problems in diagnosis and management. ML and NLP are some of the AI technologies that have been integrated into healthcare and have shown great potential in handling big data, pattern recognition, and as a decision support system in healthcare (Topol, 2019). In the management of PIDs, AI can be used to improve diagnosis by analyzing genes, detect potential biomarkers, forecast the evolution of diseases and individualize the treatment approaches (Barbouche et al., 2011). This study explores the perceptions of immunologists from GCC countries on the application of AI in the management of PIDs, clinical research, and patient care. With an understanding of AI, perceptions of the advantages, and knowledge of the problems of adopting it, this study shall provide important insights that can help to inform policy, shape resource allocation, and enhance AI applications in PID management.

2. Literature Review

Primary Immunodeficiency Diseases (PIDs) are more than 450 rare genetic disorders, which are characterized by immune system dysfunction and include patients who are more likely to have recurrent infections, autoimmune disorders and even cancer. Due to the variety of clinical manifestations and the lack of awareness, PIDs are often misdiagnosed, or the diagnosis is made late, which leads to the delay in treatment and adverse outcomes for the patient.

In the GCC region where there is limited knowledge on PIDs, the integration of Artificial Intelligence (AI) in clinical practice offers a good opportunity to improve on diagnosis, manage care and initiate precision medicine. Some of the tools that have the potential to help include those that are based on machine learning (ML) and NLP, which can help in reducing errors in diagnosis, individualization of treatment, and drug development. These advancements can greatly enrich immunologists, policymakers, healthcare institutions, and pharmaceutical companies engaged in the field.

2.1. AI in Healthcare: A Transformational Shift

This paper aims to explore the current adoption of AI in healthcare and its implications on disease diagnosis and management, drug development and clinical decision making. AI applications ranging from advanced medical imaging analysis to predictive analytics have already shown great potential in practicing medicine in oncology, neurology, and management of rare diseases (Bekbolatova et al., 2024).

AI-driven population health monitoring is important for healthcare ministries and policymakers to improve disease surveillance, increase the efficiency of resource allocation and start developing AI-powered healthcare strategies for the country. For pharmaceutical and biotech companies, AI-based platforms can assist in biomarker identification, improve clinical trials designs and enhance patient recruitment, thus decreasing the time and expenses incurred in the drug development process(Bajwa et al., 2021).

2.2. AI in PID Diagnosis and Management

The capability of AI to change the way PID care is delivered is based on its capacity to enhance diagnostic precision, individualize the treatment plan, and support clinical decision making. This is particularly important in GCC healthcare systems where the access to the specialist PID diagnostic expertise is mainly in the tertiary care centers.

• **Early & Accurate Diagnosis:** The algorithms used in the AI can process genetic data, laboratory results, and clinical information to look for patterns that are related to the subtypes of PIDs, which can lead to early diagnosis and avoid delays in diagnosis (Rivière et al., 2024).

• **Precision Medicine Approaches:** AI helps in the personalization of treatment plans by looking at the patient's biomarkers and immune system functions to

ensure that the right therapies are provided with no side effects (Johnson et al., 2021).

• **Clinical Decision Support Systems (CDSS):** Immunologists are provided with real time information by AI powered CDSS platforms that can help in diagnosing, treatment advice and risk stratification of patients based on global data. This may also assist in ensuring that there is uniformity in the management of PID care across GCC hospitals.

• **AI-Driven Drug Discovery:** Using AI-driven drug repurposing models, pharmaceutical and biotech companies can discover potential therapeutic candidates for PID treatment, which can streamline the clinical trial recruitment and regulatory approval processes (Paul et al., 2021).

It is important that AI-driven PID diagnostic tools be incorporated into national healthcare systems to significantly improve healthcare efficiency, decrease costs, and enhance patient survival.

2.3. AI in PID Research: Advancing Scientific Discovery

Biomedical research is being revolutionized by AI as it provides faster data analysis, better disease understanding, and more targeted treatment options.

• **Genomic & Biomarker Discovery:** Currently, AI-driven tools are being utilized in the discovery of disease-related genes, new PID biomarkers and the stratification of patients for targeted therapies (Bohr & Memarzadeh, 2020). This is significant to research institutions and pharmaceutical companies that are engaged in personalized immunotherapy.

• **Real-World Evidence (RWE) Analysis:** Large patient registries and electronic health records (EHRs) can be analyzed by AI powered epidemiological models to determine PID incidence and treatment outcomes in the GCC region. It is important for healthcare ministries to be able to develop AI-driven PID surveillance programs based on such data.

• **NLP in Clinical & Scientific Research:** The use of AI-based NLP models is transforming the process of extracting important information from unstructured data sources including scientific texts, clinical trial protocols, and patient notes. These capabilities help speed up medical research as well as enable the researchers and regulatory agencies to anticipate what is coming their way (Sheikhalishahi et al., 2019).

Through the adoption of AI-driven research strategies, health ministries, pharmaceutical companies, and academic institutions in the GCC can enhance their position in international immunological research and improve precision medicine.

2.4. Challenges & Opportunities in the GCC Region

Even though AI has the potential to enhance the management of PIDs and thus improve the quality of life of patients, there are issues that need to be overcome in order to ensure the integration of AI in GCC healthcare systems.

• **Data Accessibility & Standardization:** Big data and the Internet of Things (IoTs) are big data that AI models can use but only if they are given the correct and proper data. However, the current situation of data collection systems in the GCC and the lack of genomic registries are a major challenge to the application of AI in the diagnosis of PID (Rane, 2024). This means that there is a need to develop central data sharing structures.

• **Regulatory & Ethical Considerations:** This is because AI in clinical decision making requires a lot of regulations. Issues like data privacy, algorithmic bias, and ethical questions must be solved for the safe and fair use of AI (Mennella et al., 2024).

• **Healthcare Workforce Training:** Immunologists and healthcare professionals are not adequately informed on the basics of AI, which is a major challenge. For the long term, it will be crucial to sink money into education programs for AI and to develop medical curriculum with AI training.

• **Cultural & Public Perception:** The perception of AI in healthcare is not uniform across the GCC. To gain the confidence of patients and doctors, there must be proper communication, clear information, and public awareness campaigns (Mansour & Bick, 2024).

• **Industry-Academic Collaborations: Interactions** and collaborations among the pharmaceutical companies, research institutions and the healthcare ministries can enhance the use of AI. Incentives for AI-based PID research from the government and international collaboration will be important in the long run to achieve success.

2.5. The Views of Immunologists in the GCC

Getting the views of immunologists in the GCC is essential to overcome the gap between AI solutions and actual clinical practice.

This study aims to:

• Assess the level of awareness of AI-driven PID diagnostics among immunologists.

• To identify the perceived advantages and challenges of AI in the management of PID and suggest ways of overcoming the challenges to enhance the role of AI in PID care.

• Offer suggestions to the policy makers on how to incorporate AI into the national healthcare policies.

• Provide guidance to pharmaceutical companies and healthcare ministries on AI-driven drug development and clinical trials.

In conclusion, AI has the potential to change the management of PIDs in diagnosis and treatment as well as research. However, the failure of policies, wrong investments and the absence of ethical regulations will hamper the success of AI. As a result of this study, it is our hope that the findings will be useful for immunologists, policymakers, researchers, and industry leaders as a roadmap on how to leverage on AI driven PID care in the GCC countries (Alowais et al., 2023).

3. Methods

3.1. Study Design

The research method used here is a cross-sectional survey to investigate immunologist's knowledge and practice in applying artificial intelligence in the management and research of Primary Immunodeficiency Diseases (PIDs) in GCC countries. The survey is formulated to identify the current situation of AI usage and adoption, benefits and challenges, and possible uses in practice.

3.2. Study Population & Sampling

The sample comprised at least 700 licensed immunologists from Saudi Arabia, the United Arab Emirates, Kuwait, Qatar, Bahrain, and Oman. Participants were selected using several methods including:

• **Convenience Sampling:** Reaching out to the professionals through connections, medical conferences, and academic institutions.

• **Snowball Sampling:** Extending the participant recruitment through participant-referred sampling.

• **Institutional Collaborations:** Establishing partnerships with healthcare ministries, medical societies, and research organizations.

The sample comprised of immunologists from government hospitals, private health care institutions and academic medical centers to maintain the representation of different health care sectors.

3.3 Data Collection Tool

A structured questionnaire was used to evaluate critical areas of AI adoption in PID care, in the following areas:

• Demographics: Age, work experience, and previous contact with artificial intelligence.

• AI Familiarity & Usage: The current state of artificial intelligence uses in diagnosis, management, and research.

• Perceived Benefits: The potential of AI to enhance precision, productivity and individualized patient care according to participants' views.

• Adoption Barriers: Training issues, regulatory issues, costs, and data privacy issues as the main challenges to adoption.

• Future AI Applications: The anticipated use of precision medicine, predictive analytics, and disease surveillance by AI in the future.

The questionnaire was validated by experts and then tested with 30 participants before it is fully deployed.

3.4 Data Analysis

The quantitative data was analyzed using SPSS (Version 26).

4.Results.

TABLE 1 | Demographic characteristics of the participants (N = 631)

Variables	Frequency(n)	Percentage (%)
Years of Experience		
0-5 Years	*164*	*26*
06-10 years	*205*	*32.5*
11-15 years	*165*	*26.1*
16+ years	*97*	*15.4*

Table 1 provides an overview of the demographic characteristics of the participants. Majority of the participants fall within the 6–10 age group, accounting for 32.5% (N = 205), while a smaller proportion, 15.4% (N = 97), are aged above 16 years.

TABLE 2 | How familiar are you with specific AI technologies and algorithms relevant to immunology and PID management, such as machine learning, natural language processing (NLP), and predictive analytics? (N = 631)

Variables	Frequency(n)	Percentage (%)
Very familiar	*220*	*34.9*
Somewhat familiar	*365*	*57.8*
Neutral	*46*	*7.3*

Table 2: presents participants' familiarity with specific AI technologies and algorithms relevant to immunology and primary immunodeficiency (PID) management, including machine learning, natural language processing (NLP), and predictive analytics. The majority of respondents (57.8%, N = 365) reported being 'Somewhat familiar' with these technologies. The overall data suggests a positive trend in AI knowledge, indicating a foundational understanding that can be leveraged for future training and education programs aimed at expanding AI adoption in immunology and PID management. Furthermore, the presence of a substantial group of participants who identified as 'Very familiar' highlights a valuable resource for driving innovation and facilitating the integration of AI into clinical practice.

TABLE 3 | 6. How do you rate the importance of AI-based algorithms (e.g., machine learning models, deep learning algorithms) in enhancing diagnostic accuracy for PID? (N = 631)

Variables	Frequency(n)	Percentage (%)
Extremely Important	*366*	*58*
Very Important	*265*	*42*

Table 3 presents participants' assessments of the importance of AI-based algorithms, such as machine learning models and deep learning techniques, in enhancing diagnostic accuracy for primary immunodeficiency diseases (PID). The majority (58%, N = 366) rated AI as 'Extremely Important,' while all 631 respondents unanimously acknowledged AI's critical role in improving diagnostic precision, with ratings of either 'Very Important' or 'Extremely Important.' This overwhelmingly positive perception underscores the strong confidence in AI's transformative potential for PID diagnosis. Although 42% of respondents rated AI as 'Very Important,' their responses still affirm its substantial value in clinical decision-making. The unanimous recognition of AI's significance provides a solid foundation for further research, technological advancements, and broader integration of AI-driven solutions in immunology and PID management.

Figure 1: The Immunologist country of practice

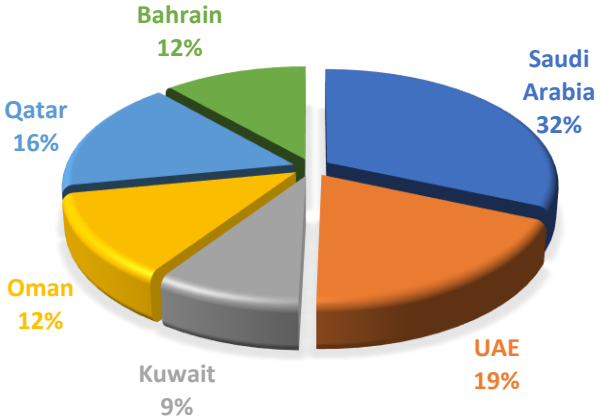

Figure 1 illustrates the distribution of immunologists' countries of practice across the six Gulf Cooperation Council (GCC) nations—Saudi Arabia, the United Arab Emirates (UAE), Kuwait, Oman, Qatar, and Bahrain. Saudi Arabia accounts for the largest proportion at 32%, followed by the UAE at 19%. Oman and Kuwait represent the smallest shares, at 12% and 9%, respectively, while Qatar and Bahrain hold moderate proportions at 16% and 12%. This distribution provides valuable insights into the regional representation of immunologists within the GCC, highlighting potential variations in workforce distribution and specialization across these countries.

Figure 2: The significance of barriers in implementing AI for PID in the GCC region

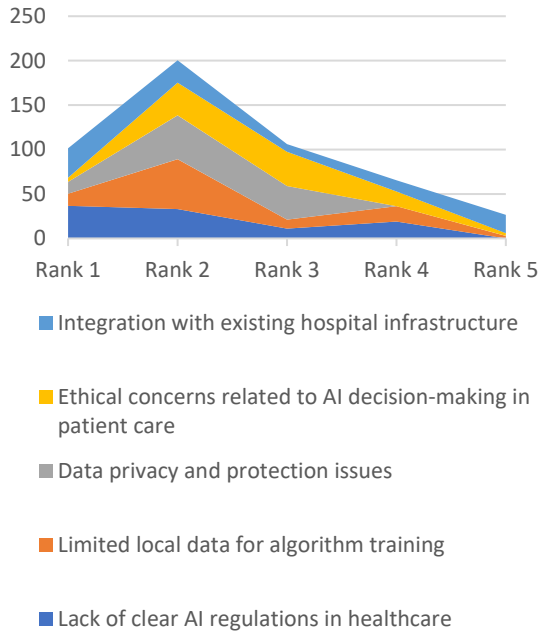

Figure 2 presents an area map ranking the key barriers to implementing AI for primary immunodeficiency diseases (PID) in the GCC region, from the most significant (Rank 1) to the least significant (Rank 5). 'Limited local data for algorithm training' and 'Lack of clear AI regulations' emerge as the most critical challenges, consistently ranking at positions 1 and 2, highlighting their role as primary roadblocks. While 'Data privacy and protection issues' remain a notable concern, particularly at Ranks 2 and 3, they are perceived as secondary to regulatory and data accessibility challenges. Ethical concerns related to AI decision-making are acknowledged as moderately important, positioned in the middle ranks. Interestingly, 'Integration with existing hospital infrastructure' is identified as a significant obstacle at Rank 1 but rapidly declines in importance in subsequent ranks, suggesting that it is a crucial challenge primarily during the initial phases of AI implementation.

Table 4: How significant are each of the following barriers in implementing AI for PID in the GCC region? (Rate each on a scale from 1–5, where 1 = Not a Barrier and 5 = Major Barrier)

	Rank 1	*Rank 2*	*Rank 3*	*Rank 4*	*Rank 5*
Lack of clear AI regulations in healthcare	36.7	33.2	11.2	18.8	0
Limited local data for algorithm training	13.6	55.9	10.1	17.4	2.9
Data privacy and protection issues	13.2	49.3	37.6	0	0
Ethical concerns related to AI decision-making in patient care	4.9	36.8	38.7	16.6	3
Integration with existing hospital infrastructure	33.1	25.2	8.4	12.5	20.8

Limited local data for algorithm training' is identified as the most significant obstacle, with 55.9% of respondents ranking it as the second most critical concern, as illustrated in Table 4 and Figure 2. This underscores the urgent need for high-quality, diverse, and readily accessible datasets to support the development of AI models in the region. Consequently, respondents highlighted 'Data privacy' and 'Ethical concerns' as the second and third most pressing challenges, with 49.3% and 36.8% of participants, respectively, citing these as major concerns. Ensuring the responsible application of AI in healthcare necessitates addressing ethical issues surrounding AI-driven decision-making while safeguarding patient data privacy.

Additionally, the absence of a robust regulatory framework emerged as a key barrier, with 36.7% of respondents identifying the 'Lack of clear AI regulations in healthcare' as the most significant

challenge. Furthermore, 33.1% of participants ranked 'Integration with existing hospital infrastructure' as their primary concern, emphasizing the need for seamless AI integration into current healthcare systems. Overcoming these obstacles is essential for the successful deployment and adoption of AI technologies in primary immunodeficiency disease (PID) management across the GCC region.

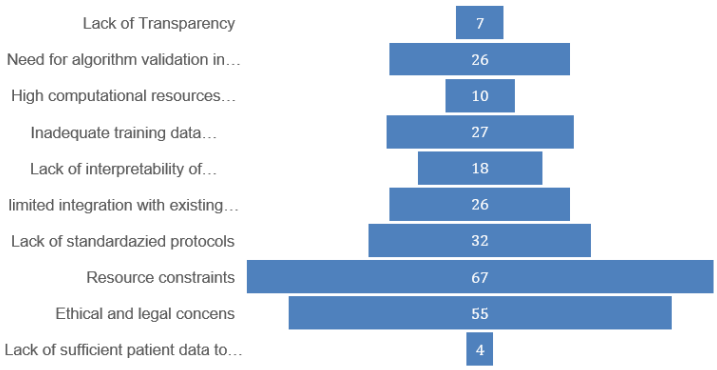

Figure 3: The biggest challenge in using AI algorithms for PID diagnosis and management.

Figure 3 highlights the primary challenges in using AI algorithms for PID diagnosis and management. Resource limitations emerge as the most significant obstacle, underscoring a critical shortage of essential assets. Ethical and legal concerns rank second, emphasizing the need for clear regulatory frameworks and ethical considerations. The lack of standardized protocols follows as the third major challenge, indicating the necessity for well-defined guidelines to guide AI development and implementation. Additionally, data-related issues—such as insufficient training data and algorithm validation—along with integration challenges, further hinder AI adoption in existing healthcare systems.

TABLE 5 | Have you used AI tools or applications in any PID-related clinical research activities? (N = 631)

Variables	Frequency(n)	Percentage (%)
Yes Frequently	*6*	*1*
Yes, occasionally	*113*	*17.9*
No. But I am interested	*512*	*81.1*

TABLE 6 | To what extent do you believe AI will become integral to PID clinical research in the next five years? (N = 631)

Variables	Frequency(n)	Percentage (%)
Very likely	*490*	*77.7*
Somewhat likely	*141*	*22.3*

Table 5 highlights a significant gap between immunologists' interest in AI and its actual use in PID-related research. While 81.1% express a strong desire to incorporate AI into future studies, adoption remains limited. Only 1% of respondents frequently use AI tools, and 17.9% use them occasionally, indicating that AI integration in this field is still in its early stages.

Table 6 reflects strong optimism about AI's future in PID clinical research. A majority (77.7%) believe AI is 'Very likely' to play a crucial role within the next five years, while 22.3% consider it 'Somewhat likely.' This widespread confidence underscores AI's anticipated impact on advancing PID research and clinical applications.

Figure 4: Top 10 AI Algorithms and Their Purposes in PID Diagnosis and Management by GCC Immunologists

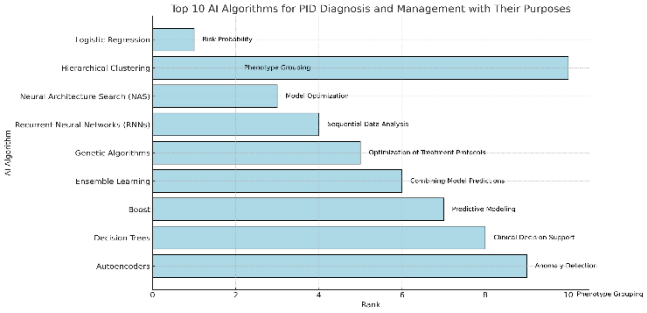

Figure 4 highlights key AI algorithms utilized by immunologists in the GCC for diagnosing and managing primary immunodeficiency diseases (PID). These models serve diverse functions, from predictive modeling to clinical decision support.

- **Predictive Risk Assessment:** Logistic regression (risk probability) and XGBoost (predictive modeling) aid in early disease detection and risk stratification.

- **Phenotype Classification & Pattern Recognition:** Hierarchical clustering

(phenotype grouping) and autoencoders (anomaly detection) assist in patient classification and rare disease identification.

- **Optimization & Personalization:** Neural Architecture Search (NAS) enhances AI model performance, while genetic algorithms optimize treatment protocols.
- **Sequential Data Analysis & Decision Support:** RNNs process longitudinal patient data, and decision trees provide interpretable clinical guidance.
- **Ensemble Learning & Integration:** Combining model predictions improves diagnostic reliability, addressing data variability and enhancing clinical utility.

These findings underscore AI's critical role in PID research and management, with a focus on improving diagnostic accuracy, optimizing treatments, and supporting clinical decision-making. However, challenges such as data availability, standardization, and regulatory frameworks must be addressed for broader adoption in clinical practice.

5.Discussion:

This study examines the potential of Artificial Intelligence (AI) to transform the diagnosis, treatment, and research of Primary Immunodeficiency Diseases (PIDs), focusing on the perspectives of immunologists in Gulf Cooperation Council (GCC) nations. While most immunologists demonstrate some familiarity with AI, its practical implementation remains limited. However, there is strong optimism regarding its future role, with the majority anticipating AI's significant integration into PID clinical research within the next five years.

Key barriers identified include the lack of clear AI regulations, limited local datasets for algorithm training, and concerns over data privacy and security. Addressing these challenges requires a collaborative approach involving policymakers, healthcare institutions, and technology developers. Establishing regulatory frameworks, enhancing data availability, and ensuring ethical AI deployment are essential for maximizing AI's potential in improving PID diagnosis and management.

6.Conclusion

This study highlights both the potential and challenges of integrating AI into PID care by analyzing the perspectives of immunologists in GCC nations. The findings underscore critical barriers, including limited clinician knowledge of AI, data availability and quality issues, and the need for robust ethical and regulatory frameworks. Addressing these challenges requires a coordinated effort among policymakers, healthcare institutions, and technology developers to ensure AI's responsible and effective adoption.

Key strategies include establishing clear ethical and legal guidelines, investing in data infrastructure and standardization, and implementing targeted training programs to enhance AI literacy among clinicians. These initiatives will facilitate the seamless integration of AI into PID diagnosis, treatment, and research, leading to earlier detection, more personalized care, improved patient outcomes, and a deeper understanding of these rare and complex diseases.

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