

Supporting quadruple aim in primary care using artificial intelligence

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Global healthcare challenges are pervasive, hindering delivery of effective, high-quality and sustainable care to populations worldwide. The quadruple aim in healthcare is a strategy to address these challenges by (1) improving population health, (2) enhancing the patient care experience, (3) reducing per capita healthcare costs, and (4) promoting the well-being of healthcare workers.¹ A resilient health system relies on sufficient, well-trained health workers, yet the World Health Organization estimates a global shortfall of 11 million by 2030, affecting all countries to varying degrees.² Achieving these aims requires innovative technologies and tools, such as artificial intelligence (AI).

AI enables machines to simulate aspects of human learning, problem-solving, decision-making and pattern recognition.³ Early AI, based on neural networks inspired by the human brain, comprises interconnected nodes that learn from data to make predictions before it evolved to machine learning (ML). ML enables computers to learn from data and make decisions without explicit programming. It is widely used for data analysis, predictive analytics and risk assessment in healthcare.⁴

Deep learning (DL), a subset of ML, employs multilayered neural networks to analyse complex patterns, excelling in tasks like medical imaging and natural language processing. Transformer models have accelerated AI, particularly in language processing and multimodal applications like image and video generation. These breakthroughs have been escalated by graphics processing units (GPUs),⁵ which enable efficient large-scale training and sophisticated model development to solve complex challenges across industries, including healthcare.⁴

Singapore is rapidly emerging as a global AI hub, adopting the National Artificial Intelligence Strategy (NAIS) in 2019 for AI development, use and governance.⁶ The local clusters of academic public primary care clinics have tapped their vast patient data and electronic medical records (EMR) systems and dovetailed NAIS to develop and test AI solutions.

Such applications, if proven to address the issues, will spread to the private general practice clinics through the primary care networks.

The current impetus to apply AI originates from a surge in chronic complex diseases amid an ageing population. Managing geriatric patients with multimorbidity is tough, compounded by the growing burden of administrative documentation in electronic systems, which are inundated with information from multiple healthcare partners. This strain contributes to widespread burnout in an overstretched healthcare ecosystem. AI is widely perceived as a tool to address these challenges, but requires clear goals, high-quality data collection, appropriate technology selection, pilot testing and ongoing evaluation.⁷ Collaboration with primary care professionals (PCPs), training and regular ethical reviews help mitigate AI bias. However, AI deployment must align with local healthcare priorities, policy directives and supported by AI expertise and resources within the primary healthcare system.⁸

Improving the health of the population

Individuals from diverse demographic, clinical and socioeconomic backgrounds can benefit from AI applications in primary care. AI facilitates diagnosis of medical conditions by speeding up reporting of laboratory and imaging results. For example, diabetic retinopathy is the leading cause of blindness in Singapore. The AI-based SELENA+ system now allows diabetic retinal imaging in primary care to be reported within minutes, which facilitates prompt referral of patients with such complication to ophthalmologists for treatment (Table 1).⁹

Neonatal jaundice (NNJ), which can cause severe cerebral damage from kernicterus in infants, is commonly evaluated in primary care facilities. BiliSG, an AI-enabled smartphone-based application, has been developed and validated to assess NNJ.¹³ It aims to decentralise NNJ management for its assessment by parents conveniently at home (Table 1).

Millions of in-person consultations were completed annually in primary care, generating huge volumes of

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Accepted: 7 May 2025

Published online first: 21 May 2025

Table 1. Summary of AI tools.

Tool name	Function	Aim	Data and preparation	Model type	Evaluation stages	Deploy plan
SELENA+ ¹⁰	Enable rapid reporting of diabetic retinal imaging	Improve patient and provider experience Improve health outcome Reduction of cost	Trained on more than half a million non-identifiable images from the Singapore Integrated Diabetic Retinopathy Programme, a screening initiative that was launched in 2010	Deep learning system	Completed extensive validation and is now commercialised	SELENA+ is currently implemented as a tool for routine diabetic retinal screening nationwide across all polyclinics
BiliSG ¹¹	Decentralisation of NNJ management	Improve patient and provider experience Improve health outcome Reduction of cost	Currently the largest study population on mobile health app to assess NNJ in the world with the data from over 500 neonates to develop the AI software	Machine learning system	Completed local validation study; commencing validation for different phone types and initiating implementation for scaling up	BiliSG will be rolled out to primary care clinics across Singapore and beyond, pending outcome of the implementation study
PREDICT.AI ¹²	To enable patients with T2DM to understand their complication risks using real-world data, and allow providers to use narrative to counsel patients on lifestyle modifications and medication adherence	Improve patient and provider experience Improve health outcome Reduction of cost	The software leverages EMR data of over 80,000 patients with T2DM who are managed in a large primary care institution	Machine learning system	Predict.AI is currently being evaluated in a randomised controlled trial	Primary healthcare professionals will be trained to use Predict.AI for scaling up across primary care clinics, pending outcome of the randomised controlled trial

AI: artificial intelligence; EMR: electronic medical record; NNJ: neonatal jaundice; T2DM: type 2 diabetes mellitus

patients' clinical, prescription, laboratory and imaging data to create risk stratification or predictive models using ML and deep learning. PERDICT.AI is a software that enables primary care professionals (PCPs) to quickly identify high-risk patients with poor diabetic control, recommend medications based on real-world effectiveness data, discuss person-centric lifestyle modifications, and facilitate shared medical decision-making.¹⁴ It is currently being evaluated in a randomised controlled trial. The intention is to adopt it as an additional tool to personalise diabetes care in the community (Table 1), which aligns with the recommendations of the Health Foundation in the UK, on harnessing AI potential in clinical practice.¹⁵

Enhancing care experience

Long wait times and limited accessibility are common barriers in primary care. AI-powered tools can improve access by streamlining remote appointment scheduling, diagnostics, and follow-ups through AI-chatbots.¹⁶ These tools relieve mundane tasks such as answering frequently asked questions like operating hours and service costs, while AI chatbots provide intuitive and personalised responses, accommodating diverse text constructs, sequencing and languages, including voice annotations. These tools empower patients and the public to access timely, affordable healthcare services efficiently.

Virtual health assistants (VHAs) are AI tools that triage and identify individuals' care needs and direct them to appropriate providers for timely management.¹⁶ With their personalisation and portability, VHAs also serve as patient companions, fostering continuity of care and empowering self-efficacy through knowledge sharing and positive motivation. These VHAs offer tailored, easy-to-understand information about specific conditions, actionable care plans, and guidance towards health goals, allowing users to address concerns on demand. Currently, these VHAs are being evaluated for the acceptance, utility, safety and effectiveness in disease management by target users.

Reducing healthcare per-capita cost

Chronic diseases are lifelong conditions requiring regular monitoring to maintain disease control and prevent complications. With their increasing prevalence in an ageing population, episodic in-person medical reviews will place increasing strain on the healthcare system. Remote telemonitoring, where patients use reliable, licensed devices to track clinical parameters and transmit data to their healthcare providers, ensures continuity of care in between clinician-patient interactions. Real-time analysis of telemonitoring data using AI can detect

abnormal trends, identify at-risk individuals for timely interventions, and address defaulters.¹⁷ AI tools further enhance telemedicine by optimising operational efficiency, reducing no-shows, managing medication supply and demand, and enabling agile deployment of trained telehealth professionals. On a per-patient basis, AI is expected to be cost-efficient, offering scalable solutions to mitigate rising shortage in healthcare manpower.

Boosting healthcare workers' well-being

During in-person consultations, AI-enabled ambient dictation technology is used in automated voice-to-text transcription, seamlessly documenting clinical notes into EMR systems.¹⁸ These digital scribes alleviate PCPs from time-consuming documentation, allowing them to focus on face-to-face interactions with patients, fostering rapport and enhancing clinician-patient relationships. Auditing the transcripts generated by these scribes requires effort, but it also creates an opportunity for PCPs to reflect on their prior patient interaction and care delivery and, if necessary, take remedial measures to address any missteps or lapses. Hence, allowing AI tools to replace repetitive manual tasks without compromising care provision and job security, which can improve staff morale and well-being, both physically and psychologically. These tools free up valuable time, enabling PCPs to spend more time with their families or pursue training for higher-value roles, enhancing their career growth and work-life balance. However, the non-deterministic nature of generative AI can introduce hallucinated or inaccurate content, which poses downstream risks to clinical decision-making. Hallucination can be mitigated through the careful use of guardrails, such as precise prompt engineering, retrieval-augmented generation and clinical finetuning. Therefore, robust validation and clinical studies are essential to select the appropriate AI solutions to ensure safety, minimise verification, and support responsible adoption.¹⁵

AI is transforming learning beyond traditional rote memorisation. AI-powered platforms, trained on extensive knowledge corpus from textbooks and medical journals, provide deep insights across a wide range of specialties.¹⁹ Instead of spending hours combing through books and papers, PCPs can now access precise, real-time answers and the latest updates through natural language platforms. Moreover, AI streamlines medical literature search and review, enabling quick access to relevant journal articles. As an e-learning companion, AI adapts to the nuances of various medical topics and personalises the learning experience, teaching PCPs intuitively and effectively to enhance their understanding and application of medical knowledge.

Transforming primary care using AI: Steps ahead

The transition to an AI-powered primary care practice requires a phased approach that integrates advanced technologies while ensuring quality care and regulatory compliance. The process begins with a comprehensive technology audit, reviewing existing systems, such as EMRs, billing software and telemedicine platforms to identify areas compatible with AI-solutions. Simultaneously, workflow and system interoperability analyses are critical to achieving seamless integration of AI tools into the practice's operations. Since many AI solutions are cloud-based, robust cybersecurity measures must be implemented to safeguard sensitive health data and prevent tampering, ensuring secure and scalable data storage systems that uphold patient confidentiality and trust.

Engaging stakeholders early to gather feedback is crucial to identify pain points within the system and prioritise areas where AI can add value. Healthcare leaders' support is vital for end-to-end AI implementation in clinical practice.²⁰ The leaders must understand the various AI systems, proactively integrating or modifying existing work routines and processes, and reviewing its deployment progress using efficiency, safety and access metric-indicators.²⁰

Equally important is training staff, including PCPs and administrators, to elevate their AI literacy.²¹ PCPs need to understand that AI is designed to assist, not replace their work. Emphasising human-AI collaboration in clinical practice can help reduce adoption resistance. PCPs should receive regular updates on emerging capabilities and new applications to stay informed and keep up with rapid AI advancements.^{21,22} Their capacity for innovative AI adoption should be considered a key attribute when hiring in the healthcare industry.

Patients and the public are also key stakeholders in AI adoption.²³ Ensuring that AI solutions are explainable fosters transparency, builds confidence and promotes wider acceptance in the community. Engaging the community through forums, continuing medical education and community platforms allows PCPs and institutional leaders to demonstrate how AI can enhance care and decision-making, debunk misconceptions, address concerns and set realistic expectations for its role in primary care.²⁴

AI implementation in healthcare has its challenges. Algorithmic bias can lead to disparities in patient outcomes, while data privacy and cybersecurity risks raise concerns about the security of sensitive medical information. Clinician resistance, often driven by trust issues and workflow disruptions, can hinder adoption. Rigorous validation is essential to ensure AI systems are accurate, reliable and aligned with clinical standards.²⁵ Addressing these challenges eases

the responsible and effective integration of AI into healthcare.²⁶

AI in primary care will evolve as developers translate innovative ideas into novel applications. Collaborating with AI solution providers and medical technology companies to co-create and adopt cutting-edge solutions is essential to stay ahead of the curve.²⁷ Partnering governmental policymakers and insurance providers to conduct cost-effectiveness analyses of AI interventions and care models will ensure fiscal sustainability for an AI-driven primary healthcare ecosystem.²⁸ Establishing AI-specific performance metric-indicators, such as patient outcomes, operational efficiency and employee satisfaction, is equally critical.²⁹ Regular audits of AI tools and systems, guided by AI engineers, experts and ethicists, minimise bias and ensure ethical use.³⁰

Primary care in Singapore is currently at the crossroads of AI transformation. Upskilling AI-trained PCPs and addressing AI fallacies improve implementation outcomes, mitigates bias risk and expedites quadruple aim achievement.

Ethics statement

Not applicable.

Declaration

The authors declare there are no affiliations with or involvement in any organisation or entity with any financial interest in the subject matter or materials discussed in this manuscript.

Keywords: artificial intelligence, care experience, healthcare cost, population health, primary care, quadruple aim, workforce well-being

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