Artificial Intelligence for Population Health and Digital Health in Singapore

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Executive Summary

As Singapore's healthcare system continues to evolve, it is crucial to leverage Artificial Intelligence (AI) to address the challenges the population faces. The A*STAR-EVYD Joint Laboratory for AI for Population Health and Digital Health ("Joint Lab"), a collaboration between Agency for Science, Technology and Research, Singapore (A*STAR) and EVYD Technology (EVYD), aims to harness the power of AI to improve public health outcomes and enhance patient care, as well as advance healthcare within Singapore's shores and beyond. This White Paper outlines the Joint Lab's mission: to develop and deploy AI solutions which address key challenges in population health and digital health. By focusing on opportunities for improving population health management, driving the growth of digital health solutions through public-private partnerships, and increasing population digital literacy, we increase the speed of successful adoption of AI in healthcare.

Policy and regulation considerations in the application of AI healthcare are crucial for balancing innovation, data privacy, and ethics. As AI's role in healthcare grows, it is essential for policymakers and regulators to develop and implement the right policies. This White Paper also outlines strategies for achieving this balance and ensuring the responsible use of healthcare AI technologies.

The Joint Lab has laid the groundwork for building an ecosystem which supports AI innovation in population health and digital health. Through an end-to-end healthcare data operating platform, coupled with AI sandbox and federated learning technologies, the Joint Lab can enable cross-institutional training, testing, validation, and deployment of AI models securely between healthcare stakeholders. This White Paper also highlights various success stories and AI use-cases, through thought pieces, as well as Feature Stories throughout the paper.

The Joint Lab hopes this White Paper will be a springboard for further collaborations, inviting interested stakeholders to the Joint Lab to harness the power of AI and make meaningful contributions to Singapore's national health and AI agenda, and build healthy societies across the world.

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Introduction

Digital Health in Redefining Population Health

Singapore's healthcare system is undergoing rapid development in the fields of Population Health and Digital Health (Ministry of Health Singapore, 2022). Population Health seeks to promote society's overall well-being, moving care to be accountable towards national health outcomes beyond traditional individual health outcomes measures. That encompasses the analysis of socioeconomic determinants, environmental effects, and public health interventions and its cost-benefit analysis in optimizing population health. There is a focus on preventive, early intervention, and health equity to include accommodation of traditionally underserved populations.

Meanwhile, digital health exemplifies technology's transformative power in improving healthcare delivery, management, and accessibility. It comprises a wide range of advances, including electronic health records, telemedicine, wearable gadgets, and health applications. Digital health not only improves clinical efficiency and accuracy, but it also empowers individuals to proactively manage their own health condition and risks factors before their physiologies transit into chronic disease states. This reflects the paradigm shift of the health system over the decade from reactive care to proactive care.

In the context of Singapore's healthcare system, both population health and digital health are critical to drive progress and address specific obstacles. Singapore's diverse population, with varying socioeconomic backgrounds and healthcare demands, emphasises the significance of a population health strategy. Data analytics and epidemiological insights can help policymakers customise interventions to vulnerable populations, reduce disparities in health care, and optimise resource allocation.

Harnessing the Power of Artificial Intelligence

In an era marked by significant demographic transitions and rising healthcare needs, the need for innovative solutions to address population health concerns is greater than ever. Across the globe, nations are grappling with a convergence of factors—aging populations, rising prevalence of chronic diseases, and these twin drivers lead to the inevitable rise of healthcare costs — and create a critical need for transformative healthcare management strategies. At the crux of this is the promise of artificial intelligence (AI), which has the potential to transform healthcare delivery, empower preventive medicine initiatives, and optimise resource allocation.

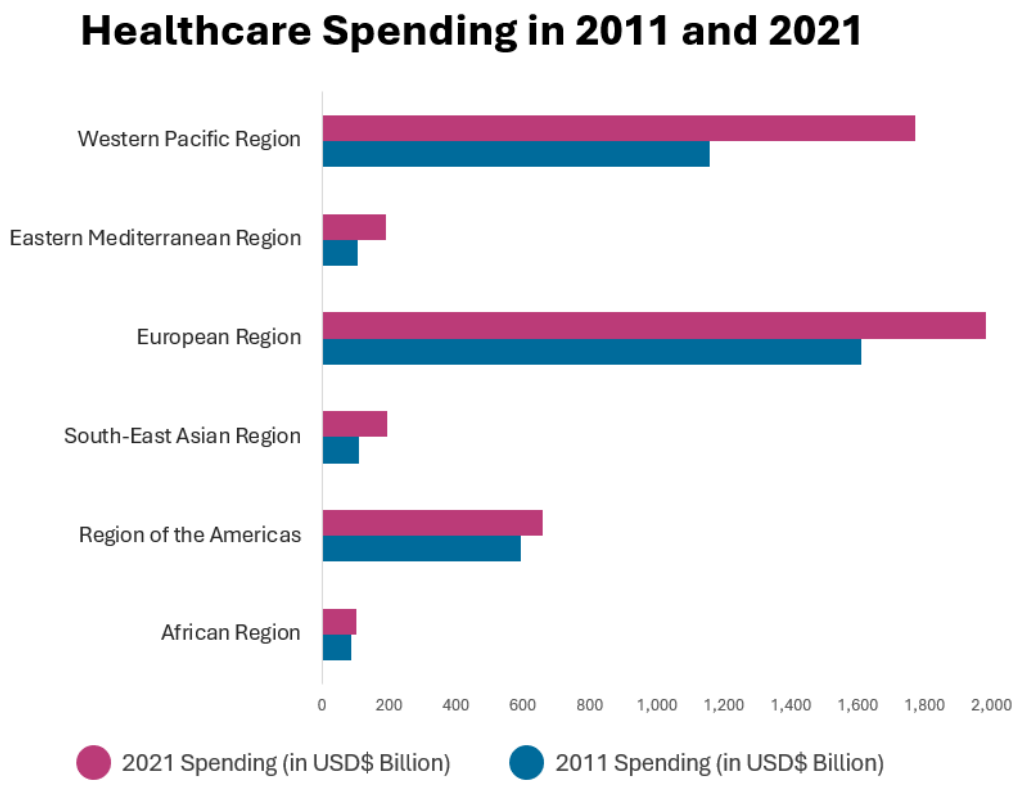

Figure 1: *Healthcare spend has increased worldwide. (World Health Organization, 2021)*

This need for transformation is more evident in many developed nations which deal with ageing populations. As life expectancy rises and birth rates fall, the demographic picture shifts dramatically, increasing the prevalence of age-related illnesses and putting tremendous burden on healthcare systems (Department of Statistics Singapore, 2023). Furthermore, the increasing prevalence of chronic conditions such as diabetes mellitus, hypertension, and cardiovascular diseases exacerbates the problem, necessitating proactive steps to reduce morbidity, disability, and premature mortality.

Against this context, AI provides a set of abilities that go beyond established healthcare paradigms. AI enables healthcare stakeholders to extract useful insights from massive amounts of data, exposing patterns and trends that human cognition cannot easily detect. By leveraging AI, healthcare providers can foresee disease trajectories, identify at-risk populations, and personalise interventions to usher in a paradigm change from reactive to preventive care. Furthermore, AI-powered solutions have the potential to relieve the financial pressures associated with rising healthcare expenses (Khanna et. al., 2022). AI enables healthcare organisations to streamline processes, improve resource utilisation, and reduce inefficiencies, lowering costs while maintaining service quality and accessibility.

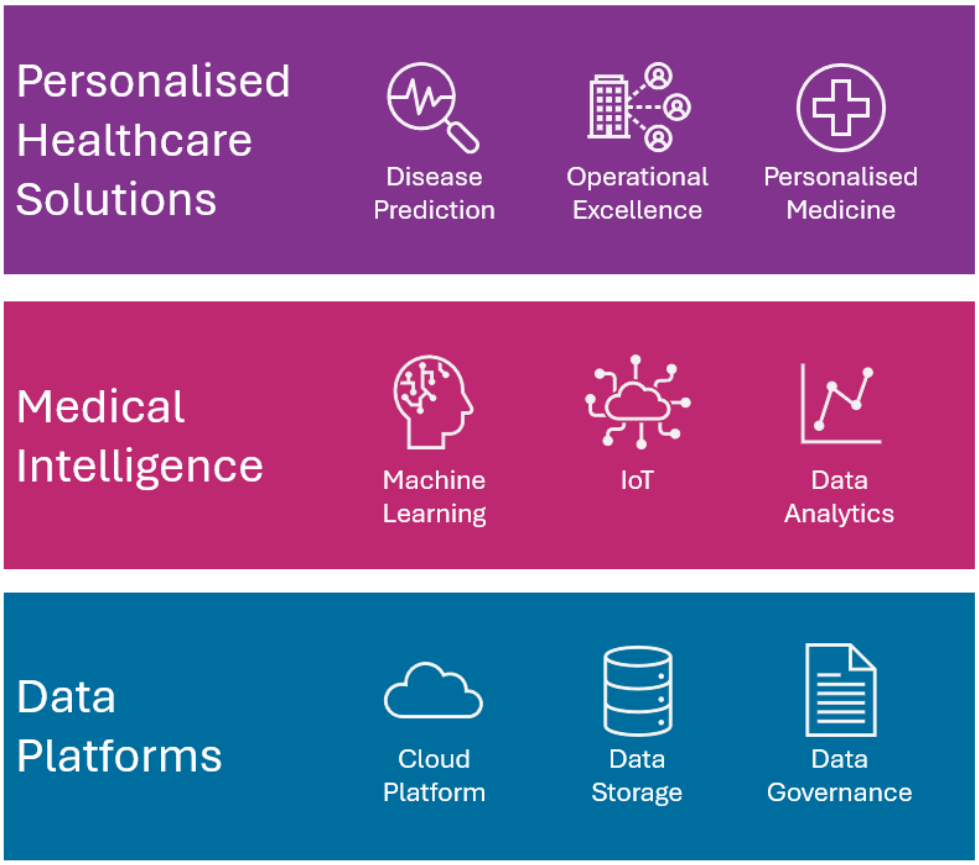

Figure 2: *An intelligent healthcare suite framework leverages robust data platforms to integrate medical intelligence and provide personalised healthcare solutions.*

The Singapore Context

As Singapore's population ages, there is an urgent need to transform healthcare delivery. In 2017, Singapore established its vision for the future of healthcare, known as the 3 Beyonds: beyond healthcare to health, beyond hospital to community, and beyond quality to value (Ministry of Health Singapore, 2018). This vision laid the groundwork for Healthier SG in 2022, aiming to shift the focus from tertiary healthcare to preventive care and population health initiatives within the community (Ministry of Health Singapore, 2022).

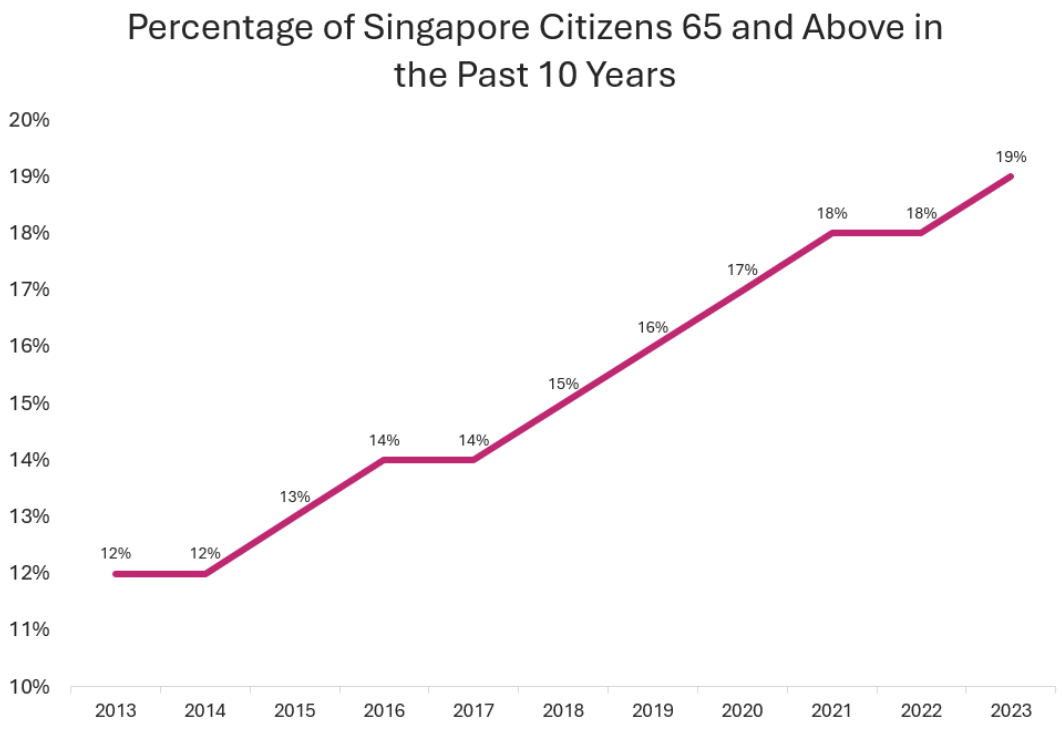

Figure 3: *The rapid rise of percentage of elderly in Singapore across a decade. (Department of Statistics, Singapore, 2023)*

Healthier SG, along with Age Well SG, are initiatives designed to support the aging population. These programs prioritize caring for the middle-aged and seniors in the community and emphasize preventive health measures to help individuals maintain their well-being. By focusing on community-based care and proactive health management, these initiatives work to ease the burden on hospitals and encourage a holistic approach to healthcare.

AI can support these initiatives and help Singapore manage its aging population's healthcare needs, promote preventive care, and ensure a sustainable and effective healthcare system for future generations. For example, Singapore's National AI Strategy (NAIS) provides innovative solutions to enhance healthcare delivery, such as Project Pensieve and SELENA+ (Smart Nation and Digital Government Office, 2024). Project Pensieve offers a novel method for early dementia detection by analysing users' drawings for potential indicators of cognitive decline. SELENA+ is a deep-learning AI system that accurately and efficiently identifies possible serious eye conditions, enabling early diagnosis and treatment. These AI-driven programs exemplify how technology can assist in advancing preventive health and community-based care for Singapore's aging population.

Introduction to the A*STAR-EVYD Joint Lab

The A*STAR-EVYD Joint Lab harnesses the joint capabilities of the Agency for Science, Technology and Research, Singapore (A*STAR) and EVYD Technology (EVYD) to accelerate digital transformation of health systems, at the axes of Population Health and Digital Health. Through combined expertise in healthcare and technology research, commercialisation and operations, the Joint Lab aims to improve Population Health outcomes by addressing healthcare challenges at a broader scale. With the use of Digital Health solutions, the transformation of healthcare delivery can greatly enhance patient-centric care and optimise the way healthcare professional work and achieve resource savings for health systems. Our expertise in developing and deploying AI healthcare tools is targeted towards revolutionizing healthcare and harnessing its power for positive economic and socially relevant impact.

Leveraging international connections in research can significantly enhance Singapore's position as a global hub for innovation and scientific inquiry, fostering collaborations that drive advancements in technology and medicine. Through the continuous expansion of the Joint Lab's partner network in Southeast Asia, Middle East, and the Americas, we foster an international milieu where our scientists and industry practitioners get diverse perspectives to enhance the quality and impact of developed AI products on the global stage.

Key Challenges in Population Health and Digital Health

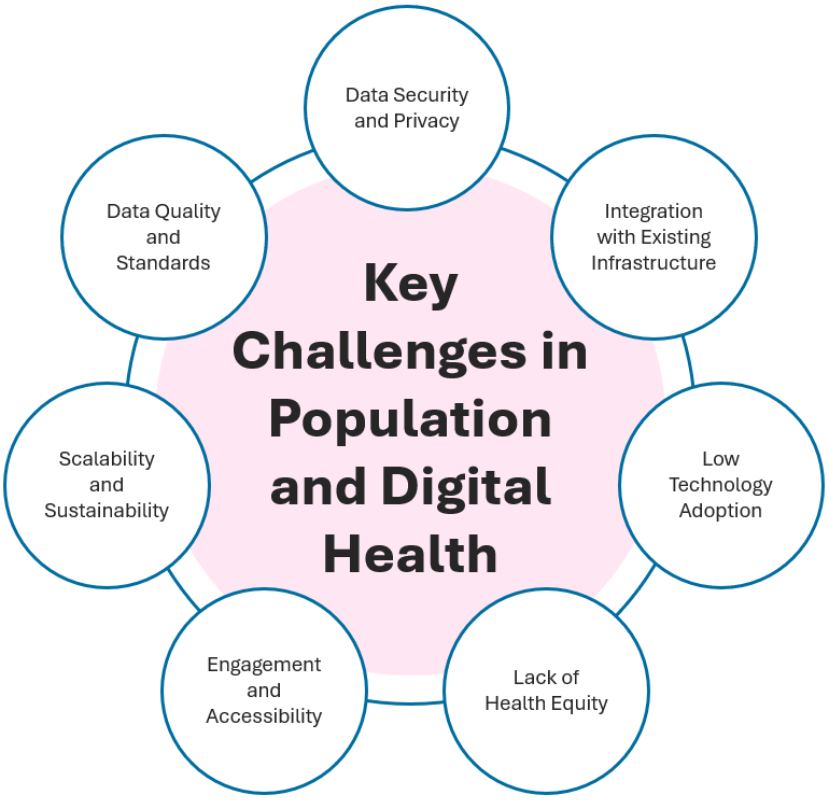

Figure 4: *Key Challenges.*

Data Security and Privacy

AI for healthcare is increasingly employed for patient care, diagnostics, and predictions of diseases. Big data and the use of Artificial Intelligence (AI) can change healthcare practice (13.8% Compound Annual Growth Rate and USD 107 billion market by 2030). However, further AI development, a data hungry process, faces challenges in data security and privacy challenges (Murdoch, 2021).

Data Sensitivity: Healthcare data is extremely sensitive, containing personal information such as medical history, treatment plans, and biometric data. AI systems require access to large volumes of data to train effectively, creating a conflict between the need for comprehensive data and the need to protect patient privacy.

Privacy Concerns: Patients are rightly concerned about the privacy and security of their medical information. AI systems deployed for data analysis must maintain individual data privacy. However, as AI algorithms become more sophisticated, there

is the risk of re-identification, where seemingly anonymized data can be linked back to specific individuals.

Data Breaches: Healthcare organizations are prime targets for cyberattacks due to the value of medical data on the black market. Integrating AI systems into healthcare infrastructures introduces new vulnerabilities which malicious actors can exploit, potentially leading to data breaches and privacy violations.

Regulatory Compliance: Healthcare systems are subject to strict regulations such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the General Data Protection Regulation (GDPR) in the European Union. AI developers must ensure that their systems comply with these regulations to avoid legal consequences.

Trust Issues: Building trust between patients, healthcare providers, and AI systems is crucial for the widespread adoption of AI in healthcare. Concerns about data security and privacy can erode trust, leading to reluctance among patients and healthcare professionals to embrace AI-driven solutions.

Data Quality and Standardisation

Data quality encompasses several dimensions that directly impact the reliability and utility of health information for decision-making.

Firstly, data accuracy and completeness stand paramount. Ensuring that data is both accurate and comprehensive is vital for facilitating informed decisions in population health initiatives. Inaccurate or incomplete data can lead to flawed analyses and decision-making processes, potentially yielding suboptimal health outcomes.

Limited accessibility is another obstacle in harnessing the full potential of health data, as data is incomplete. Factors such as privacy concerns, technical limitations, and the absence of data sharing agreements often restrict access to crucial information. This restriction impedes broader analysis and collaboration efforts, hindering progress in population health research and interventions.

Timeliness is another crucial factor in data quality. Outdated or delayed data presents inherent limitations in understanding current trends and making informed decisions. Without access to real-time or up-to-date data, healthcare stakeholders may struggle to respond effectively to emerging health challenges or evolving population health needs.

In parallel, data standardization presents formidable challenges in the realm of population health and digital health.

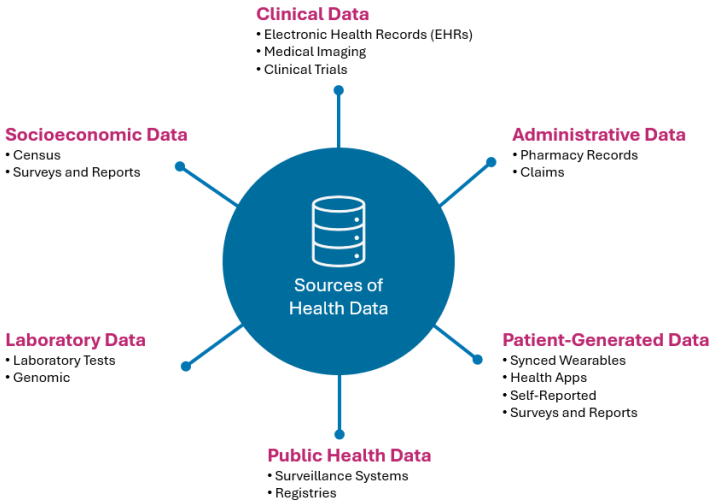

Figure 5: *Healthcare data can be derived from various sources and can be aggregated to provide a holistic view of a patient.*

Feature Story

Radiology Pathology Information Exchange Resource

Radiology and pathology archives are huge treasure troves of clinical images and reports. However, as such data are mostly in silos, the potential for AI to tap such information is limited. A*STAR's Institute of High Performance Computing (IHPC) collaborated with Singapore General Hospital to create a pathology in SGH campus, which is the largest liver transplant centre in Singapore. Using 5 years of Radiology & Pathology scan data (with about 100,000 CT scans, 7500 MRI scans, 4000 biopsy specimens, and associated medical reports) this data can be used to develop AI algorithms that can detect and describe lesion features, or diagnose abnormalities on similar imaging modalities.

Inconsistent coding practices and variations in disease classification exacerbate the challenge of data standardization and comparison data across different populations and research studies, particularly when comparing data across different healthcare information systems. These disparities hinder the seamless aggregation and analysis of health data, as discrepancies in coding practices and disease classification systems impede accurate comparisons between datasets.

The lack of common data models also hinders data standardization. Diverse data formats and structures across systems hinder seamless integration and information exchange, limiting interoperability and complicating efforts to derive actionable insights from health data.

Integration with Existing Infrastructure

The integration of new technologies with existing health IT infrastructure presents formidable challenges that demand strategic solutions to ensure seamless interoperability, data security, and comprehensive patient care.

A primary obstacle in healthcare integration is the existence of data silos, where patient information is fragmented across disparate systems. This fragmentation impedes comprehensive patient care in multiple ways. Firstly, it hampers healthcare providers' ability to access complete patient records efficiently, leading to delays in treatment and decision-making. Additionally, the disjointed nature of data storage makes it difficult to identify patterns or trends in patient health, hindering proactive interventions and preventive care efforts. To address this challenge, organizations must undertake the task of breaking down these silos and establishing interoperability and data exchange standards. By doing so, they create a more cohesive healthcare ecosystem wherein patient data flows seamlessly across various platforms and health systems, ultimately enhancing care quality and efficiency.

Interoperability issues further compound the integration process, arising from the incompatible nature of different technologies and legal and regulatory barriers. The coexistence of diverse healthcare IT systems complicates data exchange and communication, posing significant hurdles to seamless integration. To overcome this challenge, organizations can adopt universal standards such as HL7 FHIR for health information exchange (Health Level Seven International, 2021). Embracing standardized protocols facilitates seamless interoperability, enabling efficient data sharing and communication across systems, thus fostering collaboration and continuity of care.

Moreover, the integration of new technologies introduces heightened security risks, as interconnected systems increase the likelihood of data breaches and vulnerabilities. Robust security measures are imperative to safeguard patient data and preserve confidentiality. Organizations must implement encryption, access controls, and regular staff training on data security best practices to mitigate risks effectively. By prioritizing data security and adhering to stringent security protocols, organizations can ensure the confidentiality and integrity of patient information across integrated systems.

Low Technology Adoption

The slow adoption of technology among healthcare professionals and citizens is a multifaceted issue rooted in various factors that hinder the effective utilization of digital health tools.

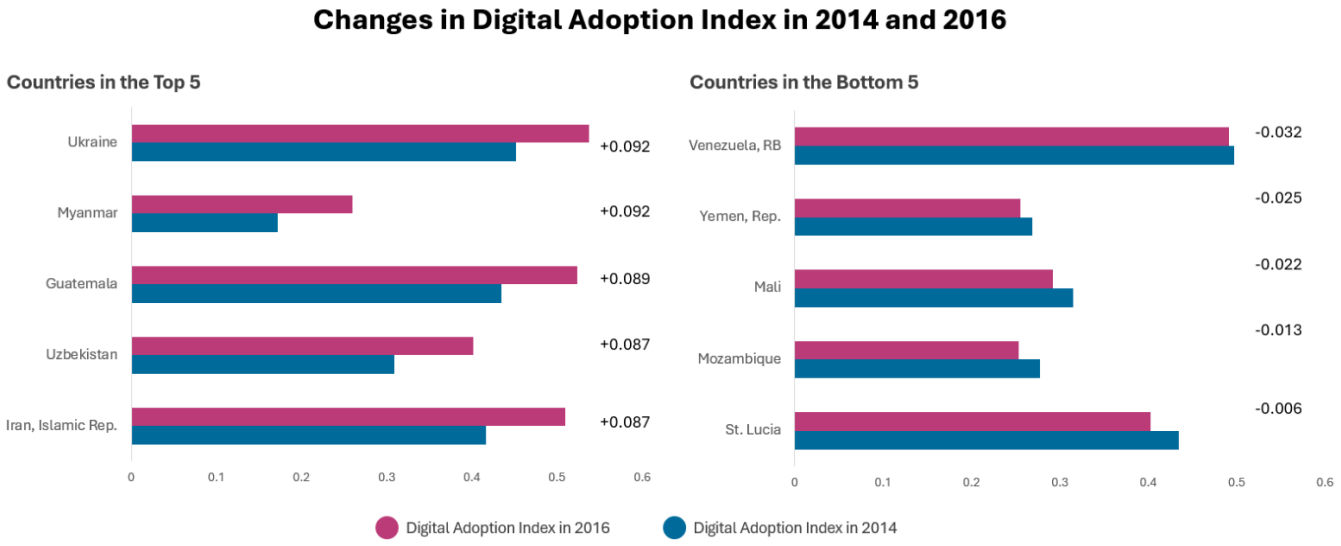

Figure 6: *Digital adoption varies across countries and conditions may worsen in low-income countries (World Bank, 2016)*

One prominent challenge is many individuals lack the necessary understanding and confidence to navigate and utilize digital health tools effectively, leading to underutilization of resources that could potentially enhance their insight or improve their quality of life. Additionally, the lack of intuitive design in digital health tools exacerbates the problem. Users may become discouraged from using a tool, or similar tools, if their initial experience is marred by confusion or frustration due to poorly designed interfaces or complex functionalities.

Moreover, scepticism surrounding digital health tools exacerbates the issue. Concerns regarding data security, privacy policies, and the legal use of data create a barrier to adoption, even among users who recognize the potential benefits of such tools. This scepticism undermines trust in the technology and increases user friction, hindering widespread acceptance and adoption.

Inadequate infrastructure poses a significant challenge too, particularly in areas with limited internet access or unreliable electricity. The lack of proper infrastructure makes it difficult to deploy digital tools effectively, limiting their accessibility to those who could benefit from them the most.

Lastly, questions about the efficacy of digital health tools persist among users. Without sufficient scientific evidence and clear communication regarding their benefits, users may harbour doubts about the effectiveness of these tools, further impeding adoption (Fischer et al., 2020).

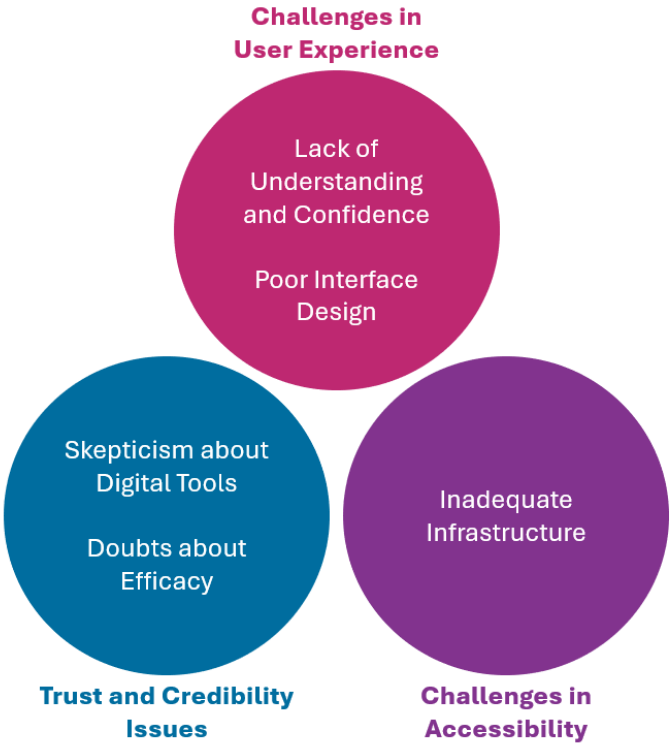

Figure 7: *Low technology adoption can be attributed to challenges in user experience and accessibility, and trust and credibility issues.*

Feature Story

aiTriage

aiTriage, a system co-developed by Singapore General Hospital and Duke-NUS Medical School, is revolutionizing emergency medical care. This AI-powered tool assists healthcare professionals in prioritizing patients based on the severity of their conditions, optimizing resource allocation, and improving patient outcomes.

One of aiTriage's standout applications is in early detection and triage of sepsis, a condition that affects millions globally. Traditionally, diagnosing sepsis involves time-consuming blood tests, which can delay critical treatment. aiTriage provides a rapid assessment tool that enables early risk stratification, allowing healthcare providers to identify and treat high-risk patients more efficiently.

aiTriage has received approval from Singapore's Health Sciences Authority (HSA), allowing it to undergo clinical trials at Singapore General Hospital (SGH). The system has also been integrated with TIIM Healthcare Platform, enhancing the triage process and supporting clinicians in making informed decisions.

The deployment of aiTriage in emergency departments is a significant advancement in medical AI technology. By providing real-time support to healthcare professionals, this system helps:

- Reduce wait times by prioritizing critical cases
- Enhance accuracy by providing data-driven insights that augment professional judgment
- Optimize resources by allocating them more effectively

aiTriage represents a transformative leap in emergency medical care, combining AI's analytical capabilities with the expertise of healthcare professionals. As it moves through clinical trials and towards broader implementation, its potential to save lives and streamline emergency care processes becomes increasingly evident.

Lack of Health Equity

Health equity remains an elusive goal for many socioeconomically disadvantaged groups. People facing discrimination based on characteristics such as ethnicity, disability, or education level often encounter formidable barriers to accessing healthcare. Factors such as systemic bias, physical inaccessibility, or insufficient financial resources, create a stark divide in healthcare access and outcomes.

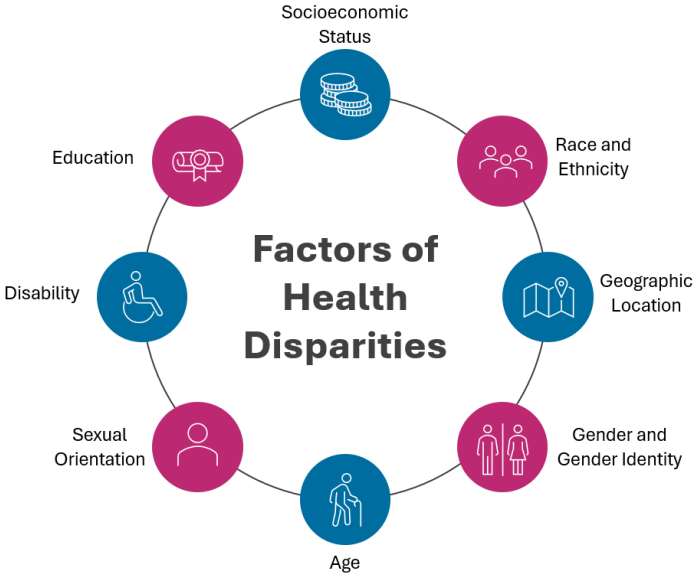

Figure 8: *The lack of health equity is a multifactorial issue that stems from demographic and socioeconomic roots.*

For underserved groups, the lack of timely and quality healthcare perpetuates chronic health disparities and preventable health issues. Without adequate access to preventive care, early detection, and treatment, individuals from disadvantaged backgrounds face a higher risk of adverse health outcomes.

This disparity is especially pronounced in low- and middle-income countries, where inadequate healthcare infrastructure and limited access to essential services and medications exacerbate health inequities. In these regions, the impact of diseases is magnified, leading to lower life expectancy and higher child mortality rates compared to high-income countries. The lack of resources and systemic challenges contribute to a cycle of poor health outcomes, perpetuating poverty, and deepening health disparities (World Health Organization, 2021; Penman-Aguilar et al., 2016).

By addressing social determinants of health, implementing targeted interventions, and leveraging digital health technologies to bridge gaps in healthcare access, we can work towards achieving equitable health outcomes for all populations, regardless of socioeconomic status or background.

Patient Engagement and Accessibility

In the context of population health and digital health, key challenges arise in promoting patient engagement and ensuring accessibility to healthcare services.

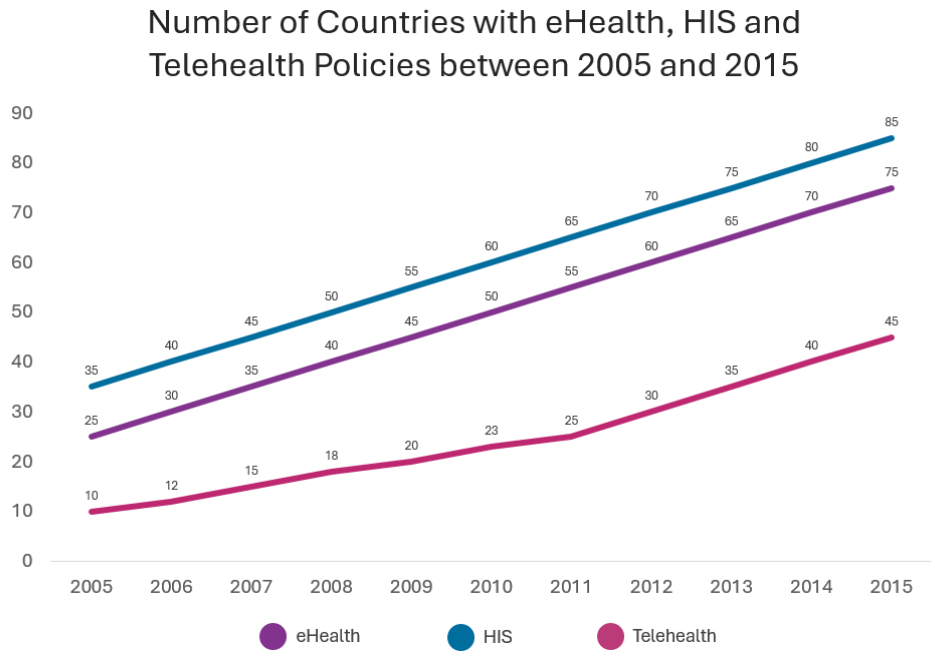

Figure 9: *More countries are adopting digital healthcare policies to improve access to healthcare services. (World Health Organization, 2016)*

Limited health and digital literacy among certain populations significantly hinder effective patient engagement and the use of digital health technologies for population health management. Without adequate literacy skills, individuals struggle to understand health information, navigate healthcare systems, and use digital tools, impeding their participation in preventive care and chronic disease management.

Motivation and adherence also present challenges in population health and digital health efforts. Patients may struggle to maintain motivation to adhere to recommended health behaviours or treatment regimens due to factors such as lack of incentives, perceived ineffectiveness of interventions, or competing demands on their time. This can undermine the effectiveness of interventions and programs aimed at improving health outcomes and reducing healthcare costs.

Additionally, the lack of user-friendly tools in digital health initiatives impedes patient engagement and accessibility. Healthcare technologies which are not intuitive, easy to use, or tailored to unique at-need populations discourage active participation in care and access to digital health resources. Without user-friendly tools, patients face difficulties managing health conditions, communicating with healthcare providers, and accessing relevant health information, limiting the impact of population health and digital health efforts.

Feature Story

mindline.sg

mindline.sg is a digital self-help platform for at-scale mental health support and early intervention for Singaporeans. The platform is developed by the MOH Office for Healthcare Transformation (MOHT) in collaboration with the Ministry of Social and Family Development (MSF), the National Council of Social Service (NCSS), the Institute of Mental Health (IMH), and the Agency for Integrated Care (AIC). Its offerings are curated in response to rising mental health concerns, particularly among young people. For this, the platform offers tools, knowledge, and pathways to self-care and professional help.

mindline.sg provides resources to support mental well-being, including an AI therapy chatbot, self-assessment tools, mindfulness exercises, and access to mental health professionals. A notable feature is "Let's Talk," a digital peer support forum that allows young people to share their experiences safely and receive support from their peers. This initiative aims to reduce stigma and encourage open conversations about mental health.

AI plays a role in mindline.sg. The AI chatbot, which comes from a partnership with Wysa, guides users in navigating to relevant CBT-inspired exercises carried out interactively with the bot. These have been adapted to the Singapore context and are bi-directionally integrated with the rest of mindline.sg. The bot knows about Singapore's resources and can signpost crisis resources, such as hotlines, if needed. AI is also being tested on the Let's Talk forum, in the Ask-a-Therapist feature. The LLM-based bot provides useful suggestions to the therapists on crafting responses and provides links to relevant self-help resources which the therapists can take into consideration.

mindline.sg has contributed to enhancing mental health support in Singapore. Through its engagement with young adults and students, mindline.sg provides users with a safe space to discuss their mental health challenges. The platform's user-friendly interface and resources make it a go-to solution for those seeking help. Additionally, mindline.sg has helped raise awareness about mental health, leading to increased acceptance and understanding within the community.

The COVID-19 pandemic highlighted the importance of mental wellness and public agencies' role in enabling access to relevant resources. We have seen growing usage of mindline.sg as more individuals sought ways to manage stress and anxiety. This success has driven further developments, with plans to expand its offerings and reach. For example, mindline.sg resources are also called on by the related HOPES app for serious mental illness. HOPES is an AI-enabled solution that encourages self-help while easing connectivity to care teams. We are beginning to see a portfolio of digital resources which can provide more effective and accessible mental health care for all Singaporeans.

Socioeconomic factors, disabilities, and age-related difficulties further exacerbate the challenges of patient engagement and accessibility in population health and digital health initiatives. Individuals from disadvantaged backgrounds may encounter financial barriers to accessing healthcare services or lack access to the necessary technology infrastructure to participate in digital health programs. Similarly, individuals with disabilities or age-related impairments may face physical or cognitive limitations that affect their ability to engage with digital health technologies or participate in population health interventions (Pfiffner et al., 2022; Henriksen et al.,2020).

Scalability and Sustainability

In the realm of population health and digital health, scalability and sustainability pose significant challenges that must be addressed to ensure equitable access to healthcare services and sustainable health outcomes.

One of the primary obstacles is the absence of a one-size-fits-all approach in medicine. Healthcare interventions and services need to be personalized to meet the unique needs and preferences of individuals, taking into account factors such as genetics, lifestyle, and socioeconomic status. However, achieving this level of personalization requires innovative approaches and resources beyond traditional healthcare delivery models.

Another critical challenge is the capacity of health systems to expand services to larger populations. As the demand for healthcare grows, particularly in the face of aging populations and rising chronic disease burdens, healthcare organizations must find ways to scale their operations and reach more people without compromising quality or efficiency. This necessitates investments in infrastructure, workforce development, and technology, as well as the implementation of innovative care delivery models that maximize resources and optimize patient outcomes.

Furthermore, while technology advancements hold immense potential to transform healthcare delivery and improve patient outcomes, accessibility remains a significant concern, particularly for lower-income segments of society. Rapid advancements in technology often lead to disparities in access, with marginalized populations facing barriers to adopting and benefiting from innovative healthcare solutions. Bridging this digital divide is essential to ensure that all individuals, regardless of socioeconomic status, have equitable access to the tools and resources needed to manage their health effectively (Sieck et al., 2021).

Opportunities to Promote Population and Digital Health

Establishing Public-Private Partnerships

The intersection of population health management and the digital health presents numerous opportunities for advancement, particularly through public-private partnerships. Leveraging the strengths of both sectors, these collaborations can effectively address critical healthcare challenges and drive meaningful improvements in population health outcomes (Strasser, 2021).

Private companies, equipped with robust infrastructure and extensive networks, offer valuable resources for scaling healthcare interventions. Their agility and capacity for rapid expansion enable the delivery of essential services to communities and uncaptured markets which may otherwise lack access to quality healthcare. Furthermore, private companies possess specialized expertise and advanced technologies which complement the capabilities of government agencies, filling in critical gaps in talent and technology to enhance healthcare delivery.

The profit-driven nature of the private sector also incentivizes the adoption of lean operating models and innovative approaches to maximize efficiency and sustainability. By optimizing resources and streamlining processes, private companies can achieve long-term viability while delivering high-quality care to diverse populations.

Exemplary models are Project ECHO in New Mexico and the Partnership for Maternal, Newborn, and Child Health coordinated by the World Health Organisation showcase successful public-private collaborations in healthcare (Mahr et. al., 2024). These initiatives highlight how partnerships between healthcare providers, academic institutions, and private organizations can improve patient care and outcomes. Additionally, endeavours such as the Health Data Consortium demonstrate how public-private partnerships drive innovation and advance healthcare through data-driven solutions, facilitating collaboration between government agencies, healthcare providers, and technology companies to inform decision-making and enhance population health outcomes.

Increasing Digital Literacy

Efforts to increase digital literacy (Arias López et al., 2023) present significant opportunities for improving healthcare accessibility and efficacy. One key avenue involves enhancing access to, understanding of, and engagement with health-related information online. By empowering individuals to access and comprehend health resources, they can better manage their health conditions and make informed decisions about their care.

Furthermore, digital platforms serve as invaluable tools for disseminating crucial healthcare information during crises. Whether they be providing updates on public health guidelines, delivering educational resources, or offering support services, these digital channels enable rapid and widespread communication of vital information to the public, promoting health literacy and resilience in the face of emerging health challenges.

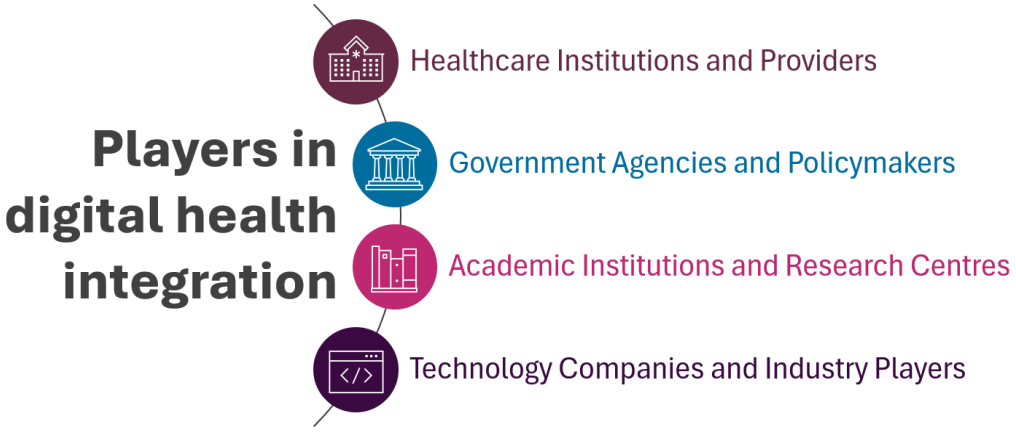

Figure 10: *Successful integration of digital health technology requires collaboration between different organisations.*

Strengthening Preventive Healthcare

The healthcare landscape is shifting towards a proactive approach, emphasizing prevention over intervention. This paradigm shift brings tremendous opportunities in empowering individuals and transforming healthcare system, and digital health stands poised to play a pivotal role in revolutionizing how we manage population health and promote preventive care (Ministry of Health Singapore, 2022).

Empowering individuals is at the heart of preventive healthcare. By leveraging wearables, health apps, and AI-powered analytics, we can provide personalized insights that cater to individual needs and risk factors. This includes real-time data collection on activity, sleep, diet, and vital signs, which enables proactive preventive measures. Moreover, accessible health education through educational apps and gamified platforms can deliver engaging, culturally relevant information on disease prevention, healthy habits, and self-management techniques, empowering individuals to take charge of their health. Additionally, remote patient monitoring via connected devices and telemedicine platforms enables remote monitoring of chronic conditions, allowing for early detection of flare-ups and facilitating timely interventions that prevent complications and hospitalizations.

Transforming healthcare systems is also a crucial aspect of preventive healthcare. By analysing vast datasets with AI algorithms, we can identify individuals at high risk for developing chronic diseases, enabling early intervention and preventative measures that improve population-wide health outcomes. Furthermore, digital health platforms can automate outreach programs, delivering personalized reminders for preventive screenings, vaccinations, and lifestyle modifications. This proactive approach improves health outcomes and reduces the burden on healthcare systems. Finally, telehealth consultations and remote monitoring can alleviate the strain on healthcare resources, optimizing resource allocation and improving access to care, especially in remote areas.

Facilitating Cross-Sector Collaboration

Cross-sector collaboration emerges as a cornerstone for driving innovation and achieving impactful outcomes. The involvement of various industries brings forth diverse expertise and resources that can be harnessed to address multifaceted health challenges and promote holistic well-being.

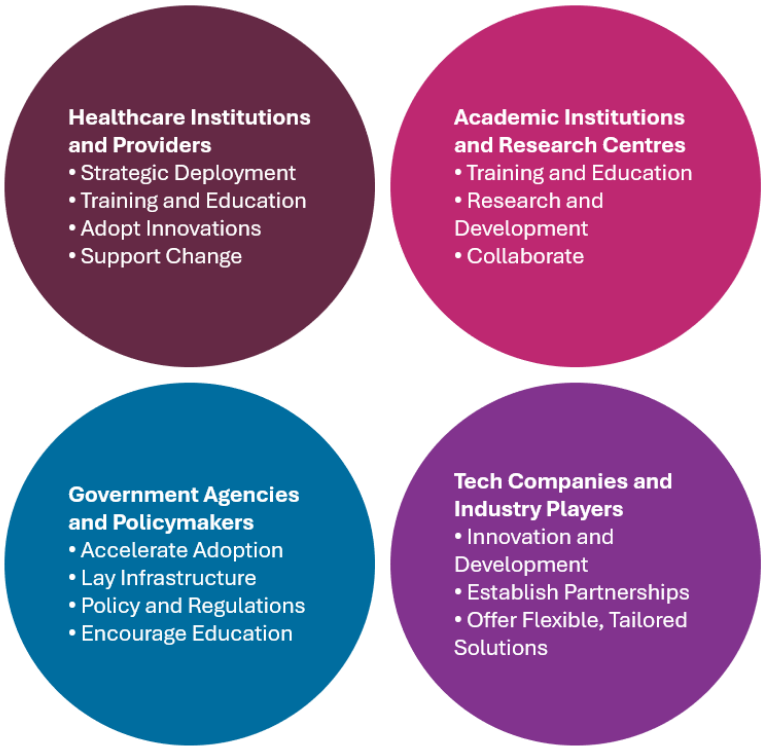

Figure 11: *Every stakeholder group plays a unique role to promote and adopt innovation in healthcare.*

Within the technology and telecommunications industry, initiatives such as telehealth services, wearable devices, and remote monitoring tools offer transformative solutions to enhance healthcare accessibility. These innovations transcend traditional geographical boundaries, enabling individuals to access healthcare services remotely and facilitating proactive monitoring of health metrics, thereby fostering early intervention and improving health outcomes.

Furthermore, engagement with financial services and insurance sectors presents opportunities for enhancing healthcare efficiency and cost-effectiveness. Collaborative efforts in fraud prevention, healthcare expenditure optimization, and the design of innovative care models can help mitigate financial risks and ensure the sustainability of healthcare systems, ultimately improving access to quality care for individuals and communities.

Moreover, partnerships with the food and agricultural industry hold potential for addressing diet-related health challenges such as obesity, malnutrition, and chronic diseases. By promoting good dietary habits and nutrition through initiatives aimed at improving diets and food choices, stakeholders can mitigate the prevalence of diet-related illnesses and foster healthier lifestyles among populations.

Establishing Regulatory Frameworks

Amidst the evolving landscape of healthcare delivery and the rapid expansion of digital health technologies, the implementation of robust regulatory frameworks is crucial to navigating the complexities of population health management.

One key aspect of regulatory frameworks is the promotion of interoperability standards, which facilitate seamless data exchange and integration across diverse health IT systems. By mandating the adoption of interoperability standards, regulatory bodies can streamline communication between healthcare providers, improve care coordination, and enhance the overall efficiency of healthcare delivery (Szarfman et al., 2022).

Moreover, regulatory frameworks can be strategically designed to align with broader healthcare goals, such as improving population health outcomes, reducing healthcare disparities, and enhancing healthcare accessibility. By incorporating these objectives into regulatory policies, governments can incentivize the development and adoption of technologies that support population health management initiatives. This alignment ensures that regulatory efforts are not only focused on compliance but also contribute to the advancement of public health objectives, ultimately benefiting individuals and communities.

Regulatory frameworks play a critical role in safeguarding patient data and privacy. By establishing standards for data security and privacy protection, regulatory bodies can mitigate the risks associated with the collection, storage, and exchange of health information. These regulations help build trust among patients, healthcare providers, and technology vendors, fostering a secure environment for the adoption of digital health solutions and promoting confidence in the healthcare system.

Integration with Traditional Care

The promotion of continuity of care lies at the heart of integrating digital health platforms in traditional care settings. By seamlessly connecting digital health solutions with established care modalities, healthcare providers can ensure a cohesive and uninterrupted patient experience throughout the healthcare journey. Patients are empowered to transition effortlessly between virtual consultations, remote monitoring, and in-person visits, thereby maintaining a consistent level of engagement and support regardless of the care setting.

AI-based risk stratification algorithms hold promise in identifying high-risk individuals and facilitating timely interventions. This enables targeted interventions to be implemented early, thereby preventing, or delaying onset of diseases as well as their complications, and ultimately improving population health outcomes.

Furthermore, the development and implementation of tailored digital health programs represent a pivotal strategy for empowering individuals to take an active role in managing their health. These programs, designed for chronic disease management, mental health support, and preventive care, equip individuals with personalized tools and resources to proactively address their health needs. By leveraging digital technologies, individuals can access comprehensive support and guidance tailored to their specific health goals and preferences.

Finally, the integration of digital health data with traditional care systems facilitates more effective population health management strategies. By aggregating and analysing data from diverse sources, including electronic health records, wearable devices, and patient-reported outcomes, healthcare organizations can gain valuable insights into population health trends and needs. This data-driven approach enables healthcare providers to target interventions, allocate resources efficiently, and address the unique needs of specific patient populations more effectively.

Neurotechnology and Brain-Computer Interfaces

Neurotechnology and brain-computer interfaces (BCIs) are increasingly relevant to digital health. Developments in hardware for both non-invasive and implantable recording of brain signals, along with advancements in signal processing and artificial intelligence (AI), has enabled technology development to better monitor, diagnose, and treat neurological conditions due to disease or injury.

Neuromodulation is an active area of research that have shown to improve symptoms of neurological conditions through neural stimulation. Our team has recently shown that stimulation of the spinal cord, in conjunction with intense rehabilitation, can help restore movement in people with hemiparalysis due to spinal cord injury. Future developments in closed-loop neuromodulation will further optimize stimulation paradigms. In animal models, we have shown that movement intentions could be decoded from cortical signals with high fidelity using spiking neural networks and long short-term memory (LSTM) networks. Importantly, we found that neural representations of movement intention are not static, but are modulated through feedback to the subject. Such movement intention can be used as a feedback signal for neuromodulation to improve both the effectiveness and efficiency of the stimulation.

Non-invasive BCIs also has many applications for health management. For example, we have collected EEG signals in people with chronic pain and have shown that we are able to detect both movement and visually evoked pain from these signals. Further, using a joint attention and pain matrix feedback training system, subjects were made more aware of their pain levels and could intentionally adopt pain relief methods in controlling their pain levels. Another example of a non-invasive BCI application is in the detection of fatigue. We have shown that an iterative learning method can be used to quantify passive fatigue, which can be used to measure fatigue in active fatigue tasks as well. Such detection of fatigue would be useful in monitoring performance and levels of stress in individuals.

Future developments in neurotechnology for digital health holds much promise as increasing number of features from neural signals are discovered as digital biomarkers for the management of well-being and in treatment of neurological disorders.

Policy and Regulation in AI for Population Health

Current Regulatory Landscape

In the realm of population health, policies and regulations concerning AI are still evolving, with a focus on ensuring the ethical and responsible use of AI technologies. Several key aspects, such as data privacy and security, ethical use, transparency and explainability, accountability and oversight, equity, and accessibility, are often addressed in these regulations.

Regulation of AI in population health varies significantly across countries and regions, reflecting diverse legal, cultural, and ethical perspectives. Some key approaches from different regions are discussed below:

- **European Union (EU):** The EU emphasizes data protection and privacy, enshrined in the General Data Protection Regulation (GDPR), which applies to AI systems that use personal data (GDPR E., 2016). The EU also focuses on ethical AI, with guidelines such as the Ethics Guidelines for Trustworthy AI developed by the High-Level Expert Group on AI, promoting transparency, fairness, and accountability (European Commission, 2019). In April 2021, the AI Act, a harmonised legal framework for AI products and services, was proposed by the EU. This Act employs a risk-based approach and classifies the use of biometric identification, sorting of patients based on their medical history, software for the management of public healthcare services, and electronic health records as high-risk AI systems. As per this Act, manufacturers would need to address the data governance and risk management for such high-risk systems (European Commission, 2021).
- **United States (US):** Regulation in the US is more fragmented, with different rules for data protection and medical devices. While the Health Insurance Portability and Accountability Act (HIPAA) provides guidelines for the use of AI in handling protected health information (HIPAA, 2021), the FDA regulates AI-based medical devices, focusing on safety, effectiveness, and quality control (FDA Centre for Devices and Radiological

Health, 2022). The Artificial Intelligence and Machine Learning Software as a Medical Device Action Plan (AI/ML SaMD Action Plan) issued by the FDA in January 2021 outlines five actions based on the total product life cycle (TPLC) approach for the oversight of AI-MD. The five actions highlight the importance of good ML practices, transparency, ways to eliminate algorithmic biases, and real-world performance monitoring (FDA, 2021).

- **Canada:** Canada emphasizes the ethical use of AI in healthcare and aims to balance innovation with privacy and security. The Personal Information Protection and Electronic Documents Act (PIPEDA) governs the collection, use, and disclosure of personal information in the private sector, including health data used in AI systems (7). The Government of Canada has proposed the Artificial Intelligence and Data Act (AIDA), which is currently before the Canadian parliament and is expected to become law in the next few months. The proposed Act addresses the design, development, and use of AI (Vayena & Fuhrmann, 2023).
- **China:** China has adopted a more permissive approach to AI in healthcare, focusing on rapid innovation and deployment. From 2019 to 2022, the National Medical Products Administration (NMPA) of China has published several guidelines that highlight the characteristics of deep learning technology, controls for software data quality, valid algorithm generation, methods to assess clinical risks, safety and effectiveness of AI algorithms, and the ability of AI-MD to aid in decision-making, such as clinical diagnosis and formulation of patient treatment plans (Song et al., 2022; Yu, 2022). The Interim Provisional Measures for the Administration of Generative Artificial Intelligence Services became effective from August 2023 in China, stipulating the development and governance of generative AI technology, service specifications, supervision, and inspection (Hu, Gong & Yang, 2024).
- **Australia:** Australia's approach to AI regulation in healthcare emphasizes patient safety, data privacy, and ethical considerations. The Australian Privacy Principles (APPs) regulate the handling of personal information, including health data used in AI systems (OAIC, 2023). The Therapeutic Goods (Medical Devices) Regulation 2002 regulates SaMDs and was recently amended in August 2021 to include a risk-based classification approach for software-based medical devices (Therapeutic Goods Administration, 2022). The Australian government is currently developing an AI safety standard and is expected to review the Privacy Act, copyright enforcement,

and enactment of online safety and misinformation legislation (Boyle & Horder, 2024).

- **Indonesia:** The Electronic Information and Transactions Law (UU ITE) governs the use of electronic information and transactions, including health data, by AI systems. The Indonesian government has launched the 20, which include guidelines for the ethical use of AI in various sectors, including healthcare in December 2023 (The Republic of Indonesia, 2008). The Ministry of Communication and Information is currently preparing a comprehensive AI regulatory framework and is expected to launch it by the end of 2024 (Muskita, 2024).
- **Singapore, Malaysia, and Thailand:** These three nations have been proactive in developing AI regulations, including in healthcare. The Personal Data Protection Act (PDPA) in all three countries governs the use of personal data, including health data in AI systems (PDPC, 2023; My Government, 2024; Suwanprateep, 2022). The Singaporean government has also published guidelines for AI ethics and governance, emphasizing transparency, accountability, and fairness (Ministry of Health, Singapore, 2022). The guidelines for SaMDs in Singapore are based on the lifecycle approach. This approach requires developers to provide the intended purpose, input data details, specifications of performance, control measures, and post-market monitoring and reporting details. The Malaysian government has launched the National AI Framework, which includes guidelines for AI development and use in various sectors, including healthcare (Ministry of Science, Technology & Innovation, 2021). The Thai government has developed the Digital Health Strategy, which includes guidelines for the ethical use of AI in healthcare (Sawasdee, 2023).

It is evident that most countries or regions provide a series of guidelines to enable the effective and safe use of AI in healthcare. Regulatory approaches are either risk-based or based on a total life cycle approach and are broadly applicable to all AI applications across all sectors of industry, not specifically for application within healthcare. In the healthcare industry, regulatory frameworks applicable to AI are merged with those of SaMDs.

Emerging Trends in AI and Population Health

Emerging trends in AI and population health, such as the use of big data, machine learning, predictive analytics, and generative AI, are likely to impact future regulatory frameworks in several ways:

- **Big Data:** The increasing availability of large datasets in healthcare, such as electronic health records (EHRs), data collected by wearables and portables, and genetic information, allows for more comprehensive analysis and personalised medicine (Price & Cohen, 2019). Regulatory frameworks will need to address the challenges of data privacy, security, and interoperability to ensure the responsible use of big data in AI applications.

- **Machine Learning:** Machine learning algorithms are increasingly used in population health for tasks such as disease prediction, patient stratification, and treatment recommendation. Regulations will need to ensure the transparency, fairness, and accountability of these algorithms, including addressing issues of bias and discrimination (Gerke et al., 2020).

- **Predictive Analytics:** Predictive analytics in healthcare can help identify high-risk patients and optimise resource allocation. Regulations will need to balance the benefits of predictive analytics with concerns about data privacy, consent, and the potential for unintended consequences (Cohen, 2014). Additionally, regulatory bodies may need to focus on rigorous validation and continuous monitoring of predictive analytics tools to ensure they remain accurate and clinically relevant over time. This could involve regular updates to regulatory submissions reflecting new training data or algorithmic modifications, like post-market surveillance in medical devices (Banegas-Luna, 2021).

- **Generative AI:** Generative AI, such as deep learning algorithms, can create new data, images, or text that mimic real-world examples. In healthcare, generative AI could have significant potential applications ranging from generating synthetic medical data and drug molecules to creating personalised treatment plans (Meskó & Topol, 2023). Generative AI often utilises large datasets, which may include sensitive patient information, to train algorithms capable of producing new, synthetic data. This raises concerns about data privacy and the potential misuse of synthetic data. Regulations like the GDPR have begun to address privacy in data usage, but future frameworks may need to specifically address the risks and controls around synthetic data generation and usage. As generative AI tools may continue learning and adapting post-deployment, regulatory frameworks will need to incorporate mechanisms for ongoing monitoring and risk assessment. The concept of a "living document" for regulatory compliance could become

standard, where updates and changes are regularly submitted and reviewed. Generative AI also raises complex intellectual property issues, particularly concerning who holds the patent rights to medical discoveries made by AI systems. Future regulations may need to define and standardise how intellectual property rights are assigned in the context of AI-generated content in healthcare (Abbott, 2016).

These emerging trends highlight the need for regulatory frameworks which are flexible, adaptive, and able to keep pace with rapid technological advancements in AI and population health. Regulations will need to prioritise the protection of patient privacy and data security while promoting innovation and the responsible use of AI to improve health outcomes. Collaborative efforts between policymakers, healthcare professionals, AI developers, and ethicists will be essential to develop effective regulatory frameworks that address these emerging trends.

Challenges in Developing and Implementing AI Regulations

Developing and implementing AI regulations in population health poses several challenges. AI technologies evolve rapidly, making it difficult for regulations to keep pace (Cohen, 2014). New AI applications in healthcare may outstrip existing regulatory frameworks, necessitating agile and adaptable regulations. Additionally, AI systems are often complex and opaque, making it challenging to assess their impact on population health and ensuring their compliance with regulations (Price & Cohen, 2019).

There are specific challenges associated with datasets. AI in population health relies on vast amounts of sensitive health data (Jimma, 2023). Regulations must balance the need for data access with privacy and security concerns. Healthcare systems often use disparate data sources and formats, making it difficult for AI systems to integrate and analyse data effectively (Panch, Mattie & Atun, 2019). Furthermore, if errors are present within the data, AI algorithms may perpetuate these errors or biases, leading to unfair or discriminatory outcomes (Price & Cohen, 2019).

AI also raises ethical concerns related to patient autonomy, consent, and the impact on healthcare professionals (Cohen et al., 2020). Developing and implementing AI regulations requires significant resources, including expertise, funding, and infrastructure. Many countries, especially low- and middle-income countries, may struggle to meet these requirements (Jimma, 2023).

Addressing these challenges requires a coordinated effort among policymakers, healthcare providers, AI developers, and other stakeholders. Regulations should be informed by ethical principles, promote transparency and accountability, and ensure that AI benefits population health while minimising potential risks and harms.

Ethical Considerations and Best Practices

AI in population health presents various ethical implications that require a comprehensive approach to develop effective and ethical policies. Below are some best practices to consider:

- **Privacy and Consent:** The use of AI in population health raises concerns about the privacy of health data and the need for informed consent. AI systems often require access to sensitive health information, and there is a risk of data breaches or unauthorised access (Price & Cohen, 2019). Ensuring compliance with data protection regulations and implementing measures to protect personal health information is essential. Anonymisation techniques should be used wherever appropriate, and regulations should address the risk of potential re-identification of anonymised data. Strengthening guidelines around data anonymisation, consent processes, and cross-border data transfers is crucial. Implementing and enforcing data protection impact assessments for AI projects can also help identify risks earlier.
- **Bias and Fairness**: AI algorithms can perpetuate biases present in the data used for training, leading to discriminatory outcomes, particularly affecting marginalised populations (Obermeyer et al., 2019). Measures to detect and mitigate bias in AI algorithms include using diverse and representative data sets, routine testing and reporting of AI systems for biases, and regular audits of AI systems by independent bodies for fairness (Rajkomar et al., 2018).
- **Transparency and Accountability:** AI systems are often complex and opaque, making it challenging to understand how decisions are made. Lack of transparency can undermine trust and accountability (Cohen et al., 2014). Ensuring transparency in AI algorithms and decision-making processes involves providing clear explanations of how the AI system works and the rationale behind its decisions (European Commission, 2019). Developing standards that require AI systems to be explainable to end-users is essential. This involves the ability to audit algorithms and the obligation to disclose the logic, significance, and implications of their outputs (Guidotti, 2019). Accountability frameworks can be established to ensure responsible use of AI systems, including clear lines of responsibility and mechanisms for redress in case of harm (Vladeck, n.d.). Policies could establish standards for a 'duty of care' in AI development and deployment, similar to those in other critical sectors.
- **Professional Roles and Autonomy:** AI may change the roles of healthcare professionals, potentially reducing their autonomy in decision-making. Ensuring that AI complements, rather than replaces, human judgment is necessary (Cohen et al., 2014). Education and training for healthcare professionals on the ethical use of AI would enable its responsible use. Policies should support the integration of AI into health systems through guidelines on professional training and certification for healthcare providers who use AI

tools. Ensuring that healthcare professionals are well-versed in the potentials and limitations of AI can enhance the safe and effective use of this technology (Topol & Verghese, 2019).

Careful consideration in the design, development, and deployment of AI in population health is required to address these ethical implications. Transparency, fairness, accountability, and inclusivity should be key principles guiding the use of AI to ensure that it benefits everyone in society. Examples of successful implementations of these best practices include the EU's Ethics Guidelines for Trustworthy AI, which emphasises transparency, accountability, and fairness, and the use of AI in the UK's National Health Service, where AI systems are designed to enhance clinical decision-making while ensuring patient privacy and data protection.

Stakeholder Engagement and Collaborations

Engaging stakeholders such as healthcare providers, researchers, policymakers, and the public, as well as fostering collaborative partnerships between governments, industry, academia, and civil society, is crucial for developing AI policies for population health. This approach offers several benefits:

- **Building Trust and Acceptance:** Involving stakeholders in the policymaking process fosters trust and transparency. When stakeholders have a voice in decision-making, they are more likely to accept and adhere to AI policies, leading to smoother implementation and adoption. Collaboration with civil society helps build public trust and ensures that AI policies reflect the values and concerns of the public, leading to greater acceptance and support for AI initiatives in population health (Hogg et al., 2023). Furthermore, engaging the public in policymaking empowers individuals to participate in decisions that affect their health and well-being. This can lead to greater public awareness, education, and advocacy for AI policies which prioritise health equity and societal benefit.
- **Ensuring Relevance and Effectiveness:** Governments can leverage the expertise and resources of industry, academia, and civil society to develop informed and effective AI policies. Industry can provide insights into technological capabilities and market trends; academia can contribute research and evidence-based recommendations; and civil society can offer perspectives from affected communities. Thus, stakeholder engagement helps policymakers understand the diverse needs, perspectives, and priorities within the healthcare ecosystem. This ensures that AI policies are relevant, effective, and address the real-world challenges faced by stakeholders.
- **Enhancing Accountability and Oversight:** Stakeholder engagement promotes accountability by providing mechanisms for oversight and feedback. This helps ensure that AI policies are implemented responsibly and that any concerns or issues are addressed promptly. Industry stakeholders

are often at the forefront of developing new AI technologies. Their involvement is crucial for pioneering innovative solutions and setting practical standards for technology use. Industry partners can contribute to developing standards that ensure AI systems are effective, safe, and transparent. For example, Google Health and DeepMind are actively involved in developing AI for health diagnostics, and their collaboration with clinical and academic partners helps ensure these technologies are rigorously evaluated (Dvijotham & Cemgil, 2023). Civil society organizations, such as patient advocacy groups, ensure transparency and accountability by advocating for patient rights and monitoring the deployment of AI technologies. For example, the Electronic Frontier Foundation (EFF) provides oversight and advocacy on issues of digital privacy and freedom, which is crucial for governing AI technology (Electronic Frontier Foundation, 2007).

- **Innovation and Technology Development:** Collaboration between various sectors can help drive innovation in AI for population health. Industry can develop cutting-edge AI technologies; academia can conduct research to advance AI applications; and governments can create regulatory frameworks to support responsible innovation. Collaborative governance models allow for the sharing of responsibilities and benefits, ensuring that ethical, legal, and social implications of AI are thoroughly considered. An example of such a collaborative model is the partnership between IBM Watson Health and the American Cancer Society, which involves multiple stakeholders in the development and oversight of AI applications in oncology (American Cancer Society, 2016). Further, collaboration helps ensure that AI policies are coherent and consistent across sectors and regions. By working together, stakeholders can align their efforts and avoid duplication or conflicting policies, leading to more effective and harmonised AI governance.
- **Balancing Innovation with Ethical Considerations:** The integration of diverse perspectives from governments, industry, academia, and civil society helps balance innovation with ethical considerations, ensuring AI technologies improve health outcomes without compromising individual rights or safety. Collaborative efforts are key to navigating the complex ethical, legal, and social challenges posed by AI in healthcare and establishing effective regulatory frameworks.

Thus, engaging stakeholders and fostering collaborative partnerships are essential for developing robust AI policies in population health. These efforts ensure that AI technologies are implemented responsibly, ethically, and effectively, ultimately improving health outcomes for all.

A*STAR-EVYD Joint Lab: Building an Ecosystem for AI in Healthcare

Overview

The A*STAR-EVYD Joint Lab partnership leverages the unique strengths of both organizations to accelerate and scale innovation in population and digital health. A*STAR, Singapore's lead public sector agency, drives forward research, innovation, and enterprise (RIE). With robust capabilities in biomedical and physical sciences, A*STAR lays the groundwork for pioneering R&D. The partnership taps into A*STAR's extensive network of research institutions and industry collaborations to push forward innovative healthcare solutions. Focusing on scalable platforms and advanced data aggregation techniques, A*STAR ensures cutting-edge research with real-world healthcare applications. This collaboration advances public health surveillance and digital health solutions, setting the stage for transformative healthcare improvements.

EVYD is a leading health technology company in Southeast Asia. Her mission is to be the best at combining technology with medical intelligence to build a future where everyone can access better health. EVYD complements A*STAR's scientific expertise with its strengths in commercialising health technologies and operations. EVYD's focus on digital health solutions and AI-driven innovations aligns seamlessly with the Joint Lab's objectives. EVYD's robust in-house expertise includes clinicians, software developers, and data scientists, who have prior working experience in government, healthcare institutions, and consumer internet companies, which enables the deployment and scaling of population health solutions in multiple geographies, including the United States and Brunei.

Together, A*STAR and EVYD prioritise education and awareness to foster a culture of innovation in healthcare. Engaging in pilot testing and deployment, they translate research findings into practical, scalable solutions that enhance patient-centric care and address broader healthcare challenges. This strategic collaboration harnesses the combined strengths of both organisations, driving economic and societal impact, address real-world needs and at the same time revolutionizing healthcare through innovative, sustainable practices.

EVYDENCE: Foundation Health Data Operating Platform

EVYD's proprietary Data Operating Platform, EVYDENCE, is a comprehensive, end-to-end solution for healthcare data management, governance, and security. Its innovative features and robust infrastructure empower healthcare organisations to harness the full potential of their data, transforming fragmented healthcare data into actionable insights. EVYDENCE integrates seamlessly with various data sources, ensuring high accuracy in data cleansing and structuring. The platform excels in data management through its scalability and serves as the foundational platform to be built upon for downstream data-driven and AI applications.

In terms of data governance, EVYDENCE utilises medical AI to enhance data quality and integrity, providing comprehensive insights tailored to healthcare needs. The platform's patient search capability allows for efficient retrieval and analysis of a patient's complete data view, further aiding informed decision-making. Additionally, EVYDENCE supports proactive data governance by enforcing, role-based access controls, data standards, and compliance requirements, ensuring that all data handled meets the highest quality and regulatory standards.

Security is a cornerstone of EVYDENCE, with robust measures ensuring data protection and compliance with regulatory standards. Its cloud-agnostic architecture offers flexibility and control over data sovereignty, enabling secure storage and processing of sensitive healthcare information. The platform employs advanced encryption methods and continuous monitoring to protect against data breaches and unauthorised access, ensuring the confidentiality and integrity of healthcare data.

Furthermore, EVYDENCE facilitates better population health management by integrating diverse data sets, including clinical, claims, and social determinants of health. Such comprehensive data integration enables healthcare providers to gain deeper insights into patient populations, identify trends, and implement effective interventions. By leveraging predictive analytics and machine learning, EVYDENCE helps in forecasting health outcomes and resource utilisation, thus optimising healthcare delivery and reducing costs.

The platform also emphasises the importance of user experience by providing intuitive dashboards and visualisation tools. These tools allow healthcare professionals to easily interpret data and derive meaningful insights without requiring advanced technical skills. This user-centric approach ensures that data-driven decisions are accessible to all stakeholders within the healthcare ecosystem, from clinicians to administrators.

Moreover, EVYDENCE supports interoperability by adhering to industry standards and protocols, facilitating seamless data exchange between different healthcare systems. This interoperability is crucial for creating a cohesive healthcare

environment where data flows effortlessly, enhancing care coordination and patient outcomes. The platform's ability to connect disparate systems and standardise data ensures that healthcare providers have access to complete and accurate information at all times

With the rise of AI comes additional considerations for data platforms to facilitate robust development of healthcare AI model. Besides the considerations mentioned above such as data governance, interoperability, and security, Data Operating Platforms will need to embed features to allow AI models trained to undergo rigorous validation to ensure their accuracy and reliability, so they can be used in the various settings. Localisation, and regular monitoring, are also required to ensure AI models adapt and are tailored to specific regional populations and stay clinically relevant over time. The AI models will also need be explainable for them to allow healthcare professionals and patients to understand the logical rationale to derivation of outcomes and predictions from the AI model, to achieve adoption of AI in clinical settings. These requirements contribute towards AI governance in the future, and the EVYDENCE Platform will undergo upgrades with these capabilities, to facilitate such AI governance in the future.

Collaborative Partnerships

Collaborative efforts in AI model training enable institutions to pool diverse datasets, creating comprehensive global models that represent varied populations. This approach fosters inclusive solutions, mitigates healthcare disparities, and addresses global population health challenges. Privacy-preserving technologies facilitate such collaborations by ensuring data sharing without compromising patient privacy, reducing legal constraints, and minimising costs related to network bandwidth and infrastructure. Vast, diverse data sets support advancements in precision medicine, enabling AI-driven models to deliver personalised healthcare interventions tailored to individual patient needs, thus improving overall patient outcomes.

Key stakeholders in the healthcare industry who need to collaborate include healthcare institutions and providers, government agencies and policymakers, academic institutions and research centres, and technology companies and industry players. Healthcare institutions and providers offer insights into clinical workflows and patient needs, guiding the development of practical AI tools. Government agencies and policymakers help navigate regulatory frameworks and ethical considerations, ensuring compliance and fostering trust. Academic institutions and research centres drive innovation and validate AI efficacy through rigorous studies. Technology companies bring expertise in AI development, data management, and technical support, enabling healthcare organisations to leverage advanced technologies for improved patient care and operational efficiency.

Building on the importance of collaboration and model validation, the integration of AI sandboxes and federated learning capabilities further enhances the development and localisation of AI models for diverse healthcare applications.

Collaborative efforts extend beyond technical co-development to alignment of real-world needs and priorities. Engaging healthcare stakeholders, such as providers and patients, helps identify pain points and guide AI development efforts, ensuring that resultant tools are relevant to address real-world needs.

The Joint Lab's Healthcare AI Symposium will provide a platform for sharing experiences and allow cross-pollination of ideas for adaptation in different settings, spark new collaborations. Publications such as this White Paper on AI in Population and Digital Health will allow the dissemination of latest trends, insights, and best practices in healthcare AI. All these endeavours allow collective learning in the healthcare ecosystem's journey towards advanced, inclusive, and relevant AI solutions in healthcare.

AI Sandbox and Federated Learning Technology

Collaboration is important for AI development. As described above, healthcare AI and machine learning models require rigorous validation and localisation to ensure their effectiveness across different populations and geographies. Validation involves verifying that the AI model performs well on data that is independent of the training dataset, highlighting its ability to generalise to new, unseen data. This is crucial because a model trained on data from one specific population might not perform accurately on another population due to differences in genetic, environmental, and socioeconomic factors. For example, an AI model developed for predicting cardiovascular risk in a European population may not be directly applicable to an Asian population without proper validation and adjustments to account for genetic and lifestyle differences. (Youssef et al., 2023; Wang et al., 2023)

Localisation further adapts these models to specific geographic and demographic contexts, addressing variations in healthcare practices, disease prevalence, and patient behaviour across regions. This process often involves retraining or fine-tuning the model using local data to ensure its predictions are relevant and accurate for the target population. For instance, a machine learning model for diagnosing neurological disorders developed in the U.S. would need to be localised for use in China by incorporating local patient data and considering regional healthcare practices. (Yang et al., 2022; Wang et al., 2023)

Moreover, the need for targeted validation emphasises the importance of contextual relevance. Models must be tested in the specific settings where they will be deployed to ensure they meet the local healthcare standards and effectively address the unique needs of the population. This approach helps in identifying any discrepancies or biases that may arise due to the model's original development context, thus ensuring more accurate and equitable healthcare outcomes across diverse patient groups. (Sperrin et al., 2022; Youssef et al., 2023)

AI Sandbox for Healthcare

Institute of High Performance Computing (IHPC) is pioneering a unique collaboration with Singapore's healthcare cluster to create an AI sandbox - a simulated, real-world clinical environment that enables innovators and developers to test their AI solutions in a safe and controlled setting.

The Clinical Sandbox provides anonymised clinical data sets for AI developers to validate their models' applicability and generalisability to the Singapore population. This ensures that AI-powered solutions are tailored to meet the specific needs of Singapore's healthcare system. Meanwhile, there is a Technical Sandbox designed specifically for clinical-tested algorithms (e.g. FDA or HSA approved) to be tested in

a simulated environment, ensuring seamless integration with existing systems and deployment readiness.

As part of the A*STAR-EVYD Joint Lab effort, A*STAR's Institute of High Performance Computing (IHPC) is working with EVYD to integrate the AI Sandbox with EVYDENCE data governance platform to scale up this solution. By accelerating both development and deployment, this innovative sandbox will drive breakthroughs in AI-powered healthcare solutions that improve clinical outcomes, enhance patient experience, and reduce healthcare costs.

Federated Learning for Multi-Institution Collaboration

Worldwide, healthcare AI is being increasingly employed for patient care, diagnostics, and disease prediction. Currently, however, AI model development and training is predominantly realised on local datasets within institutional data silos., and results in limited predictive power of such AI models.

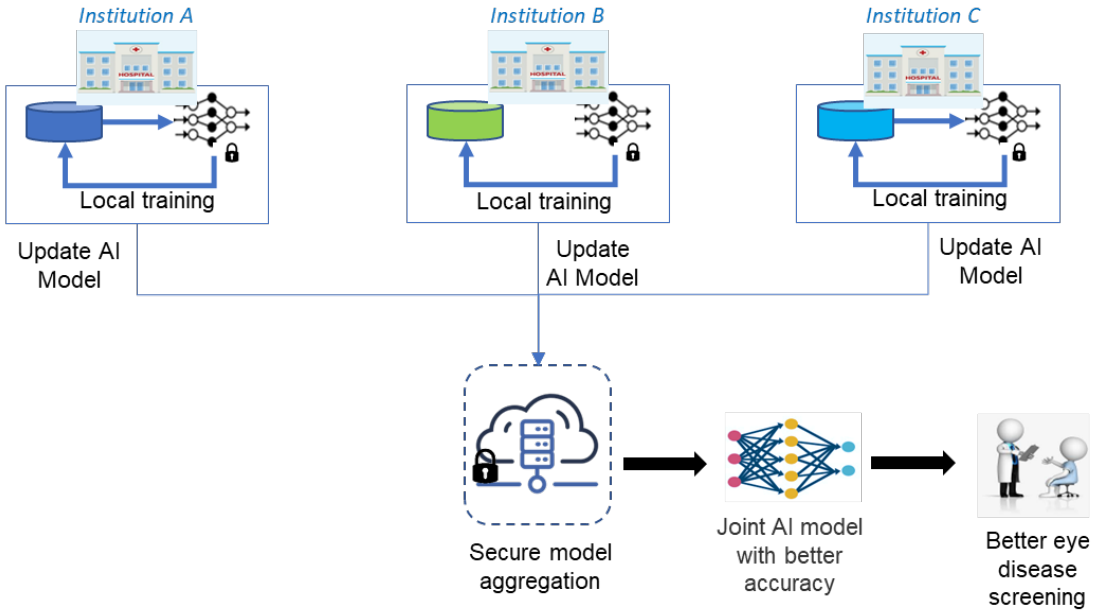

***Figure** 12 How Federated Learning can enable better outcomes with decentralised machine learning across various institutions.*

Federated Learning (FL) allows healthcare AI developers from one institute to train their models together with healthcare AI developers from other institutions using separate datasets, without having to extract data out of, or exchange the data between different systems. This decentralised machine learning framework, with secure model aggregation, is especially important for healthcare, where patient data privacy is priority.

EVYD is collaborating with IHPC in the development of FL technology, through the improvement of convergence, generalisability, and model accuracy in heterogenous network architectures, as well as the development of privacy-preserving schemes for FL. That has contributed to FedPro, an end-to-end privacy-preserving platform leveraging FL for multi-institutional digital health collaborations. In this instance, blockchain technology ensures a decentralised, secure, and trustworthy environment for model training and aggregation. Smart contracts and blockchain's transparency incentivise data sharing while maintaining privacy with techniques such as differential privacy and multi-party computation, resulting in a more accurate and robust AI model for medical diagnostics without compromising data confidentiality.

Healthcare AI Applications

Categorisation of AI Applications

Innovative AI technologies have transformed the healthcare landscape, unlocking new possibilities for improving patient outcomes. The A*STAR-EYVD Joint Lab has focused on some key areas where AI can drive meaningful change including large language models (LLMs), multimodal AI with foundation models, physics-based AI, and reliable AI.

LLMs can be used to provide accurate medical information, assist in early detection and triaging, and offer personalised recommendations for self-care strategies and therapy options (Clusmann et al., 2023). For instance, AI-powered health assistant system can provide timely responses to health related queries based on the latest medical literature and guidelines. LLMs can also be used in data processing to improve the data integrity and quality for downstream AI model and data analytics use cases.

Multimodal AI with foundation models integrates various sources of medical data to provide comprehensive analyses, enabling doctors to make more informed decisions. Foundation models have garnered significant interest from both research and industry sectors due to their substantial potential in healthcare applications. These models can be trained with large amounts of unlabelled or weakly labelled data, such as medical images, reports, and Electronic Medical Records (EMRs), without the need

for explicit data annotation. This capability offers numerous advantages, including reduced dependency on data annotation for fine-tuning and the ability to generalise effectively in real-world scenarios across diverse cohorts, ethnicities, and devices. The Institute of High Performance Computing (IHPC) has made significant strides in applying multimodal AI with foundation models to ophthalmology. One example is the development of UrFound, a retinal foundation model that learns universal representations from multimodal retinal images, including fundus images and Optical Coherence Tomography (OCT) scans, alongside domain knowledge. UrFound has demonstrated strong generalisation ability and data efficiency when adapting to various downstream tasks in retinal imaging analysis.

Physics-based AI integrates existing physical laws and physiological systems into AI models to achieve hybrid models with higher robustness and explainability while requiring less training effort. This approach is particularly useful in modelling complex systems, such as within medical imaging, or in mitigating environmental variations and demographic disparities. Embedding fundamental physical principles into AI models ensures they adhere to known scientific constraints, leading to more accurate predictions.

Reliable AI focuses on developing AI systems that are trustworthy, robust, and dependable. Key aspects include ensuring robustness against attacks and mitigating biases. For instance, privacy-preserving AI platforms facilitate multi-institutional collaboration in digital health while ensuring data privacy (Wang et al., 2024; Kanagavelu et al., 2022). Additionally, robust data management, ethical considerations, and safety measures enable the use of AI systems without compromising confidentiality.

Use Cases

AI's potential applications in healthcare is wide ranging. In the realm of disease diagnosis and prevention, there is medical imaging AI which can be rapidly and accurately analyse scans to detect abnormalities for review by clinicians. There is also potential for early disease risk prediction. Through aggregated patient clinical, lifestyle and behavioural data across various sources electronic medical records, with understanding of patient behaviour presence of lifestyle risk factors (such as sedentariness, low physical activity, and caloric excess), and data, will enable prediction of risk for health issues and major debilitating diseases such as strokes and heart attacks.

AI is also able to optimise treatment adherence and augment the patient experience by simplifying self-monitoring tasks by patients. For instance, AI-assisted imaging for vital signs determination uses facial video recordings to non-invasively monitor blood oxygen saturation and blood pressure. Further development work is undertaken in aiding early detection of diseases such as heart failure.

Another example of treatment optimisation is in the management of atopic dermatitis, also known as eczema. It is a disease characterised by dry, itchy, and inflamed skin patches. IHPC has collaborated with KK Women's and Children's Hospital in Singapore (KKWCH) to develop an AI solution which allows self-monitoring of eczema using their mobile devices, assessing eczema severity levels based on skin photographs, and also suggesting treatment strategies. The application of such AI can include acne monitoring and skin cancer detection.

AI's use in patient care can be seen in clinical severity assessment with Medical Triaging AI. Co-developed by IHPC in collaboration Singapore General Hospital (SGH) and the Singapore University of Technology and Design (SUTD), it leverages the advanced capabilities of a novel Medical Knowledge-Grounded Large Language Model (Medical-LLM), including natural language understanding, contextual comprehension, and text generation, to engage in interactive conversations with patients. It will ask follow-up questions, clarify ambiguities to gather comprehensive patient health information, and provide personalised recommendations to triage the patient at home. The Triaging AI system is scheduled to undergo pilot testing in SGH's SGH@Home Programme, through the Dr. Buddy mobile health application, which incorporates remote patient monitoring.

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Outcomes

Population Insights with Public Health Surveillance

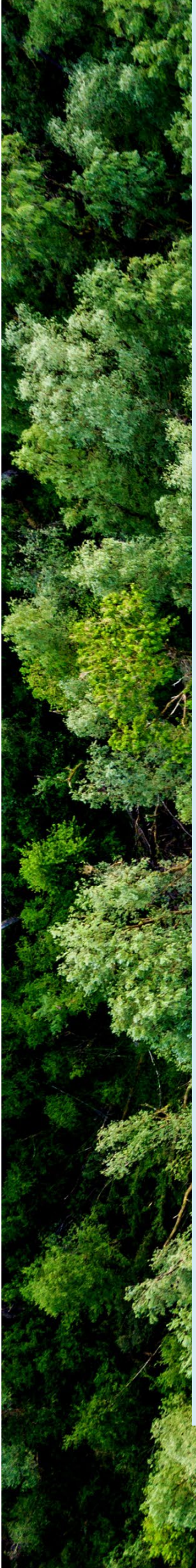
Envisioning the impact of the Joint Lab's initiatives on population health outcomes, public health outcomes, and disease prevention, several positive effects emerge.

At the heart of this revolution lies the power of predictive analytics. Its advanced algorithms and data analytics enable healthcare providers to pinpoint individuals predisposed to certain conditions, provoking targeted interventions that stave off illness. These timely interferences promise to extend life expectancy and enhance quality of life by halting the progression of chronic diseases and preventing secondary complications, while simultaneously reducing disease prevalence and the burden on healthcare systems. All in all, fostering a healthier society and alleviating the strain on the healthcare workforce.

Empowered with knowledge of comprehensive health, patients become stewards of their own health, making informed decisions, and fostering a paradigm shift towards proactive health management. This shift not only enhances individual outcomes but also heralds a new era of proactive, inclusive healthcare.

Predictive analytics at the individual level can accurately forecast the onset of health conditions, enabling early interventions, and preventing disease progression. This shift towards personalised healthcare strategies means treatments are tailored to each patient's unique needs, enhancing efficacy, and reducing side effects compared to traditional broad-spectrum treatments (Musich et al., 2014).

On a population scale, AI-powered solutions expand healthcare access through telehealth services, breaking geographical barriers and promoting health equity. Non-invasive AI-driven screenings facilitate early disease detection, optimising resource allocation by targeting interventions to those most in need. These AI solutions excels in their capacity to monitor population health trends and intervention effectiveness, allowing for proactive measures and real-time strategy optimisation to address emerging health threats and public health risks.



Feature Story

Disease Surveillance in Brunei Darussalam

By repurposing EVYD's system built to track COVID-19 cases during the pandemic, EVYD launched a Public Health Surveillance (PHS) platform in Brunei Darussalam to track infectious disease and non-communicable diseases in the country. Utilising AI based tools to clean and aggregate real-world data from various systems, we can currently track more than 45 diseases in real-time through intuitive dashboards. The system enables spatiotemporal surveillance, and can calculate, through AI algorithms, outbreak risk of infectious diseases and identify high risk clusters through segmentation. These findings can be standardised into a tailored reports which are automatically sent out to relevant parties for further action. Through the prompt sharing of data, the system can enhance global health security, shape health policies, and increase public awareness about health issues, ultimately improving a country's health outcomes and ensuring better management of both immediate and long-term health challenges.

The platform has been used to create comprehensive disease registries in Brunei for four non-communicable diseases: cardiovascular diseases, diabetes, cancer, and endocrine disorders. These registries consist of targeted patient lists as well as disease-specific metrics created through collaboration with clinicians in Brunei, leveraging on EVYD's medical intelligence. Through AI-based algorithms, disease-specific metrics such as longitudinal chronic kidney disease (CKD) staging, are created which provides clinicians with actionable insights for informed decision-making. Subsequently, disease registry data are used to power tailored disease dashboards to visualise trends in non-communicable diseases using spatiotemporal maps and demographic distributions.

Healthcare System Efficiency and Cost Control

A primary benefit of AI in healthcare lies in its ability to predict and detect diseases early. Advanced algorithms help to identify at-risk individuals before conditions worsen, hence saving treatment costs, ensuring efficient allocation of resources, and leading to long-term savings.

Population health surveillance, powered by monitoring of health trends and disease patterns, enhances the efficiency of healthcare systems. By identifying and addressing emerging health issues carefully, resources and budgets are used more effectively, preventing costly outbreaks or epidemics. Surveillance also informs policymaking, helping to refine interventions and optimise resource allocation, therefore maximising the efficient use of healthcare resources.

Large-scale screening programs, enabled by digital health tools, offer significant cost savings through low-cost, non-invasive methods. Targeted screenings identify those who need immediate assistance, avoiding unnecessary expenditures and directing resources to those who need them most.

Lastly, digital tools and predictive models provide clinicians with real-time insights, guiding them to deliver personalised and effective care. These tools offer second opinions and evidence-based recommendations, improving patient outcomes and reducing costs from ineffective or unnecessary treatments.

Patient Care and Experience

By analysing diverse datasets and generating personalised health plans, individuals are put in charge of their health journeys, boosting health literacy and proactive behaviours. This tailored approach ensures timely, effective treatments with minimal risk of side effects or complications.

Integrating digital tools into healthcare delivery revolutionises the field by enhancing convenience and accessibility through remote consultations and monitoring. This first and foremost benefits those with limited mobility or in remote areas.

The continuous monitoring of chronic conditions is a cornerstone of the Joint Lab's initiatives. Wearable devices and remote technologies provide real-time health feedback, enabling early detection and immediate intervention: Ultimately helping patients treat their conditions carefully. The seamless exchange of information between patients and healthcare teams through digital platforms enhances patient engagement and empowering self-management, leading to better health outcomes and a more positive care experience.

Conclusion

The intersection of AI and population health holds immense promise for transforming Singapore's healthcare system. The Joint Lab for AI for Population Health and Digital Health, a collaborative effort between A*STAR and EVYD, is poised to accelerate this transformation by creating an ecosystem that fosters innovation, collaboration, and responsible adoption of AI-powered solutions.

The Joint Lab will continue to address key challenges in population health and digital health, including data security and privacy, integration with existing technological infrastructure, and regulatory frameworks, and in deployment of AI technologies with a focus on sustainability, reducing their environment impact. By leveraging its unique strengths of a strong foundational data infrastructure, AI algorithm development, and collaborative partnerships, the Joint Lab will develop and deploy cutting-edge solutions which improve healthcare outcomes, enhance patient care, and reduce costs.

The impact of the Joint Lab's initiatives will be far-reaching, with expected benefits extending to public health outcomes, healthcare system efficiency, patient experience, research, and development in AI for health, and Singapore's position as a global leader in AI for health. As the Joint Lab continues to expand its international outreach, including partnerships in Brunei Darussalam and UAE, it is well-positioned to drive meaningful change in the global healthcare landscape.

Ultimately, the success of the Joint Lab will depend on its ability to foster a collaborative eco-system which brings together stakeholders from diverse backgrounds and with varied, deep, expertise. Through closer collaborations, healthcare stakeholders can harness the transformative power of AI to create a healthier, more sustainable future for all Singaporeans, and inspire similar efforts globally.

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