Incorporating AI into cardiovascular diseases prevention–insights from Singapore

Mayank Dalakoti,[a,b,c,*] Scott Wong,[d] Wayne Lee,[d] James Lee,[d] Hayang Yang,[a,b] Shaun Loong,[a,b] Poay Huan Loh,[a,b,c] Sara Tyebally,[a,b,c] Andie Djohan,[a,b,c] Jeanne Ong,[a,b,c] James Yip,[a,b,d] Kee Yuan Ngiam,[d,e] and Roger Foo[a,b,e]

[a]Cardiovascular Research Institute, National University Heart Centre, Singapore
[b]Cardiovascular Metabolic Disease Translational Research Programme, NUS Yong Loo Lin School of Medicine, Singapore
[c]Ng Teng Fong General Hospital, Singapore
[d]Group Chief Technology Office, National University Health System, Singapore

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Summary

Improved upstream primary prevention of cardiovascular disease (CVD) would enable more individuals to lead lives free of CVD. However, there remain limitations in the current provision of CVD primary prevention, where artificial intelligence (AI) may help to fill the gaps. Using the data informatics capabilities at the National University Health System (NUHS), Singapore, empowered by the Endeavour AI system, and combined large language model (LLM) tools, our team has created a real-time dashboard able to capture and showcase information on cardiovascular risk factors at both individual and geographical level- CardioSight. Further insights such as medication records and data on area-level socioeconomic determinants allow a whole-of-systems approach to promote healthcare delivery, while also allowing for outcomes to be tracked effectively. These are paired with interventions, such as the CHronic diseAse Management Program (CHAMP), to coordinate preventive cardiology care at a pilot stage within our university health system. AI tools in synergy allow the identification of at-risk patients and actionable steps to mitigate their health risks, thereby closing the gap between risk identification and effective patient care management in a novel CVD prevention workflow.

Keywords: Artificial intelligence; Preventive cardiology; Primary care; Primary prevention; Cardiovascular disease; Cardiovascular risk factors; Population health

Cardiovascular disease prevention and mitigation–a pressing need

As we emerge from COVID-19, we must not lose focus of other public health priorities. Amongst them is the ongoing epidemic of cardiometabolic diseases. For every life taken by COVID-19 in the last three years, at least seven more have been claimed by cardiovascular disease (CVD).[1] This trend continues to rise over the last few decades across the world, and not any less acutely in Singapore.

Singapore has recognised the need for better prevention strategies when adopting the "life cycle model" of population health. Healthier SG is an ambitious nationwide initiative to increase focus and resources towards preventive care. The shift of our healthcare model from a fee-for-care model towards a capitation model underscores the Ministry of Health's (MOH) efforts to create a clearer and proactive preventative strategy.[2] The premise of such a strategy is that care of individuals after the point of a major diagnosis such as CVD is costly to both patient and the healthcare system. Even though secondary and tertiary prevention remain important, improved upstream primary prevention would enable more individuals to lead lives free of CVD and their complications, including heart failure, arrhythmias, and death. This would also enable cost and resource saving for the healthcare system, and overall lead to a healthier population. As such, the healthcare system has had to take a more proactive approach to primary prevention of CVD.

Limitations in the current practice of CVD prevention and mitigation

Passive vs proactive approach to prevention

In the current passive model of healthcare, most individuals seek medical attention only upon the onset of symptoms and signs suggestive of manifest CVD. Conversely, those with cardiovascular risk factors (CVRFs) and a high likelihood of CVD may be asymptomatic, such as those with poorly controlled diabetes or hypertension. There may not be a perceived urgency to achieve aggressive risk factor control that would require a concerted effort from both the patient and managing clinical team. As such, a more proactive approach is called upon, where individuals with CVD risk beyond

*Corresponding author. National University Heart Centre, 5 Lower Kent Ridge Road, S119074, Singapore.
E-mail address: mayank_dalakoti@nuhs.edu.sg (M. Dalakoti).
[e]Co-senior authors.

a set threshold may be automatically identified and highlighted for proactive and evidence-based interventions by their treating teams. That said, there must be a buy-in from various stakeholders across the healthcare system for this approach to work. For the patients, this acknowledges the key role that they would have to play in advocating for their own health, even at the expense of more scrutiny over their health status by their healthcare providers. For primary care physicians, this may mean additional work to review patients automatically flagged for poor control of CVRFs or unaddressed CVD risk. For cardiovascular specialists, this would mean stepping out of the tertiary hospital and clinic settings where they are most comfortable, to engage in earlier conversations on CVD risk and working collaboratively with colleagues and resources in the community. For the healthcare system, there would be added upfront cost as more individuals would be accessing limited healthcare resources, with the hope that this would lead to downstream saving of cost and increase time spent in good health.

The overall task of CVD preventive care has to be distributed amongst the key stakeholders in a fair and equitable way to avoid further overloading primary care practitioners (PCPs), overwhelming patients without their complete buy-in, and increasing the workload of the entire healthcare system.

Addressing social determinants of health in an equitable way

In Singapore and worldwide, it is increasingly recognised that differences in social determinants are inextricably linked to health equity and outcomes.[3] In high-income countries, income level, education, employment status and neighbourhood socioeconomic status (SES) are major influencers of CVD outcomes.[4] Singapore is no different, and neighbourhood SES has been found to be highly correlated with health outcomes and adequacy of treatment.[5] As institutions and societies grapple with ensuring equity in the design of healthcare delivery, we must ensure the solutions we implement do not exacerbate existing equity gaps but bridge them. Interventions targeting individuals and groups traditionally undertreated first requires identification of those at highest risk, and those who current services and interventions are unable to reach. Until recently, real-time electronic health data to inform primary, secondary, and tertiary CVD prevention, available at both geographical and individual level, has not been available. Such information linking social determinants to medical records would enable targeted prevention campaigns.

Enabling convenient and accessible CVD primary prevention across the spectrum of primary to specialist care

Whilst healthcare practitioners are generally based in the hospital or clinic setting, most of our at-risk population exists in non-healthcare centric communities. Earlier studies have shown that engaging individuals in their communities is vital to improve quality of care.[6] With an increase in ageing populations worldwide, coupled with multiple other health priorities, approaches to interact with at-risk individuals in their communities would have to be efficient, cost-effective, and convenient to the individual. Healthcare solutions would also have to be designed to offload the burden on primary care practitioners. At the same time, a key enabler is the adoption of technology, particularly in high-income nations. Singapore has a 93.7 percent penetration of smartphones,[7] providing a key opportunity to use technology to provide solutions delivered to the individual, through their phones and devices.

Exciting opportunities for artificial intelligence (AI) to fill the gaps in CVD prevention and healthcare delivery

With the ongoing rollout of HealthierSG, most Singapore healthcare providers will soon be connected on a common electronic medical record (EMR) platform. A shared EMR will serve as the interface between primary care, allied health professionals and cardiologists and other specialists.

Our team has deemed an incontrovertible need to harness digital and AI solutions in the delivery of preventive cardiology services, and to address the current gaps in CVD prevention.[8] If done properly, this promises to enable strategic data-driven digital solutions delivered to the doorstep of individuals across the continuum of CVD risk, yet also improve equity by the identification of high-risk and under-treated individuals and groups.

With the rapid progression of AI and machine learning approaches, we are now equipped to enable deep learning on large, population level databases. This holds tremendous potential in many aspects of clinical medicine, such as in providing solutions to automate routine care and aid clinical decision making. Yet, there remain challenges in its implementation, in part due to a lack of large-scale trials, governance and infrastructure. Crucially, healthcare service design must ensure that the benefits of AI are experienced throughout the spectrum of care from the patient to the PCP and the specialist. At our institution, we have set out to harness the potential of AI in a novel CVD prevention workflow, paying close attention to these gaps and considerations. Supplemental Fig. S1 details how the AI solutions exist within the AI tribrid architecture at our institution, including the Discovery AI and Endeavour AI layers. Box 1 describes the tools and use cases. Importantly, only individuals with direct provision of care for individuals have access to their identifiable information within the designated layer, and on a need-to-know basis. This strict access control ensures that privacy of

Box 1.
Artificial intelligence tools deployed within NUHS.

AI tool	Description
Endeavour AI (EAI)	A stream capable AI tool developed within the NUHS Cluster that allows for deployment of multiple microservice applications to service various users. It allows for an integrated approach to data streams to interface with the electronic medical record (EMR) system to deliver cutting-edge AI tools to assist in healthcare delivery. Example use case includes live streaming of cardiovascular risk factors or admissions to emergency department
Discovery AI (DAI)	A database in the NUHS cluster allowing processing of data, and development of AI tools and algorithms. Example use cases include display of cardiovascular risk factors over a recent period of time, automated calculation and display of cardiovascular risk scoring systems through EMR
Large language models (LLM)	A deep-learning AI model which can understand, summarise, translate, predict, and generate text and other content based on the datasets at NUHS. Example use case includes enabling EMR-based automated messaging to clinical team and patients

sensitive data is protected while allowing for possible benefits of the novel system to be realised.

Achieving improved visibility for targeting CVD risk using CardioSight

With the impetus to deliver a new approach to healthcare delivery, a collaborative team was set-up to create the data infrastructure and systems that would allow the demonstration of real-time, integrated and automated CVRFs and other healthcare data, as well as a pipeline for a step-wise implementation of healthcare delivery protocols to improve CVD prevention for our patients. Dedicated data analysts work in tandem with clinicians to identify appropriate clinical data sources and data streams, which are then encoded onto a live dashboard. Our data analysts employ the use of large language models during coding and debugging, to increase the speed of production while retaining the accuracy of data. Putting together the data informatics capabilities at the National University Health System (NUHS), Singapore, empowered by the Endeavour AI system, CardioSight is a real-time dashboard able to capture and showcase CVRFs together with other key data at both individual and geographical level for individuals accessing healthcare within the NUHS. The final dashboard is a Streambased AI, which can interface in real time with our healthcare cluster's EMR system to achieve live feeds of all inpatient and outpatient data for real time analysis and visualisation. By automating many of these processes, this reduces the reliance on extensive manpower for data collection and analysis and allows relevant and up-to-date data interpretation for clinical management (Fig. 2 and Supplemental Fig. S1).

Real time data on traditional CVRFs are pinned on a geographical heat map alongside their nearest primary care providers, providing a heat map to target individuals depending on their levels of cardiovascular risk. Integration of data from complementary but distinct components of the EMR, such as medication records and data on area-level socioeconomic determinants (e.g. housing type) allow a whole-of-systems approach to promote tracking of clinical risk and subsequent healthcare delivery, while also allowing for population-level outcomes to be tracked effectively in the long-run. CVD risk calculators such as the Qrisk and Singapore-Modified Framingham Risk Score (SM-FRS) can also be calculated enmasse in real time. Furthermore, patients lost to follow-up with unaddressed CVD risk can be detected and automatically flagged to their healthcare providers, potentially addressing a key challenge of current healthcare delivery systems. In its complete form, CardioSight allows an overall comprehensive oversight of CVD risk and other key data at individual and population-level. This forms the afferent limb of the novel CVD prevention healthcare delivery system. Together with its efferent limb that will be covered in the next section, Cardiosight supports the execution of personalised yet high-level preventive cardiology initiatives within our healthcare system. Importantly, knowledge of baseline epidemiology of CVD and CVRFs will allow assessment of the effectiveness of ongoing interventions over not just a geographical location but also across a timeline.

Cardiosight was finalised in July 2023 and has been in deployment since September 2023 as part of a larger endeavour of disease-specific capabilities, such as diabetes and chronic kidney disease. It is currently in pilot trials for use in CVD prevention since Dec 2023. Based on early assessment, one key priority is that of CVRF optimisation for purposes of primary CVD prevention in high-risk groups such as individuals with diabetes. As shown in Fig. 1A and Supplemental Table S1, a significant proportion of the population of those with diabetes treated within NUHS have risk factors not treated to target. There is also a geographical over-representation of some of these patients in certain areas. These would represent key groups and individuals to deliver preventive interventions, which can be localised. Another key priority is CVRF optimisation in patients with prior myocardial infarction. Fig. 1B and Supplemental Table S2 detail both the proportion of such individuals not at target LDL-C, as well as their geographical distribution, to allow for interventions to be delivered to them.

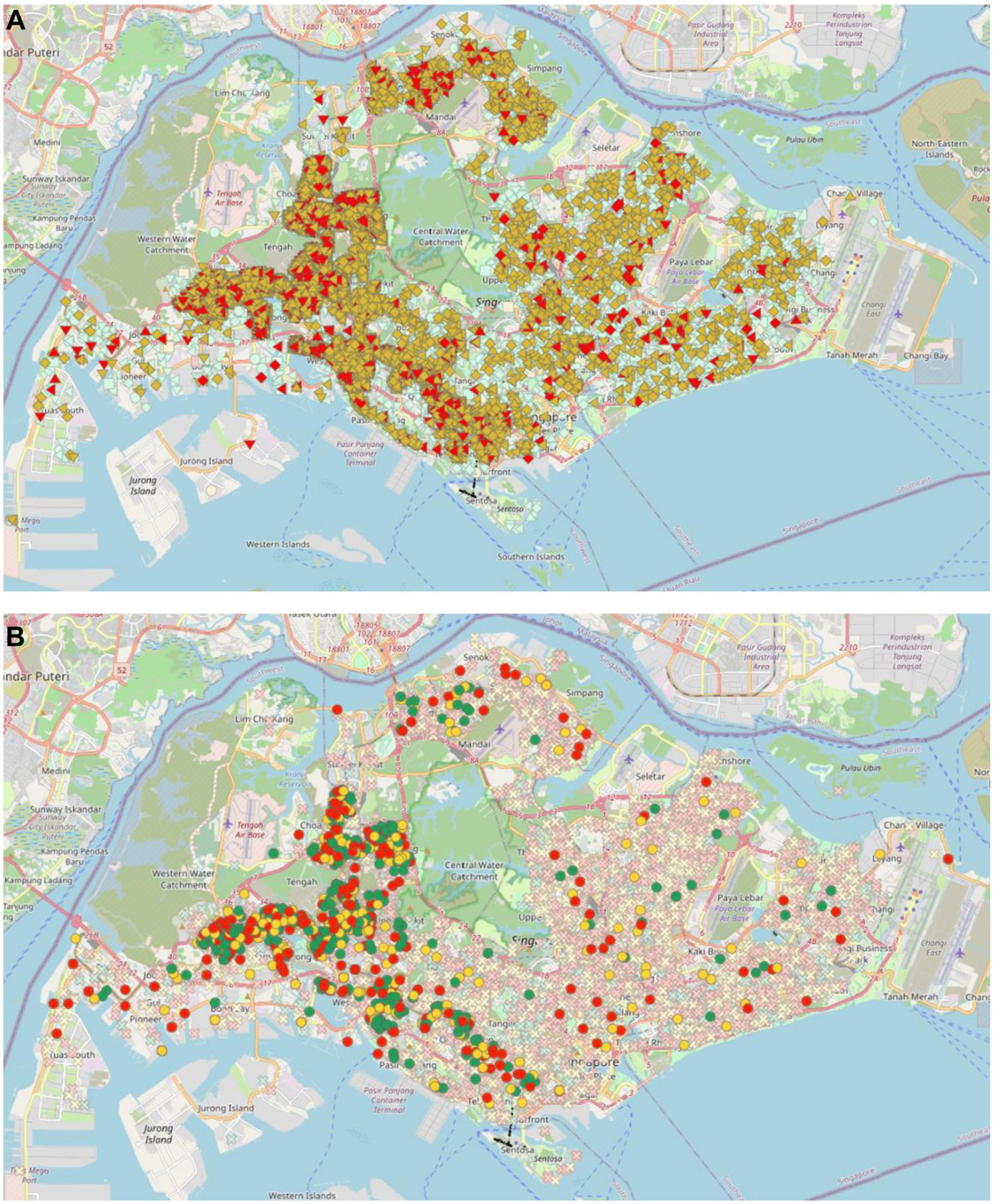

Fig. 1: **A) CardioSight geospatial map of individuals with diabetes.** A geospatial map highlighting all HBA1c and LDL-C values of 93,200 individuals with diabetes in the National University Health System, Singapore from 1/6/23 to 31/10/23. HBA1c is colour coded, where Light green spots represent HBA1c < 7%, yellow spots represent HBA1c 7–10%, and red spots represent HBA1c > 10%. All patients have LDL-C above the target of 1.8 mmol/L. **B) CardioSight geospatial map of patients with prior diagnosis of myocardial infarction.** LDL-C levels in 1096 patients with international classification of diseases (ICD) code diagnosis of Myocardial Infarction are highlighted from 1/6/23 to 31/10/23 mapped to residential location. Green spots represent LDL-C = /< 1.8 mmol/L (target LDL-C), yellow spots represent LDL-C 1.8–3.0 mmol/L, red spots represent LDL-C > 3.0 mmol/L. Overall, 725 (66.1%) of patients have LDL-C above a target of 1.8 mmol/L, and 105 (9.5%) patients are not on statins.

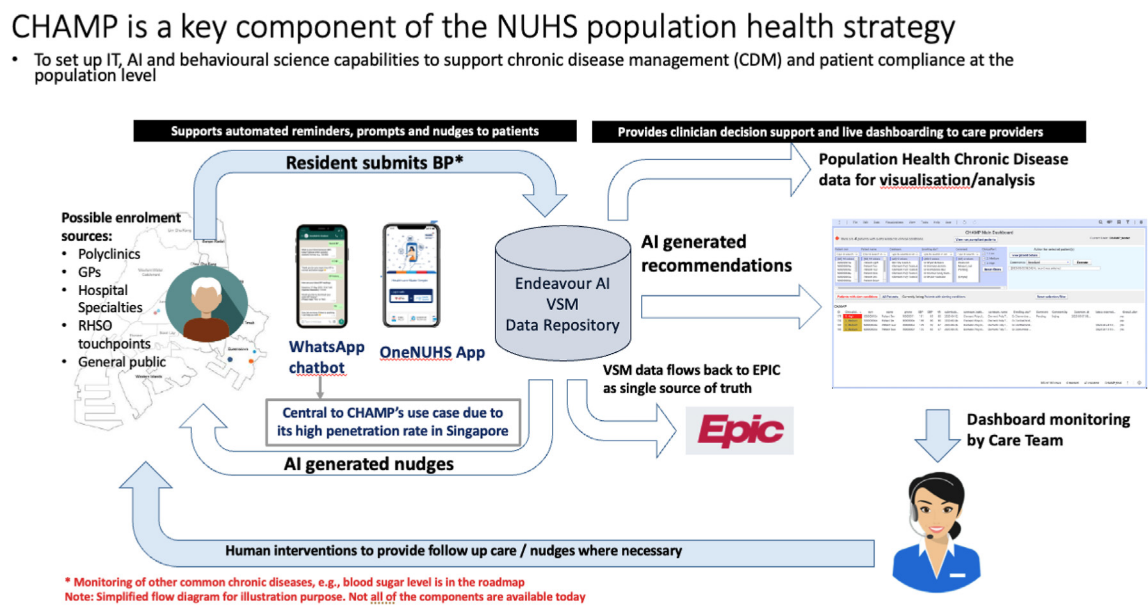

Fig. 2: Integration and consolidation of different sources of data via National University Health System CHronic diseAse Management Program (CHAMP).

CardioSight has its own limitations and challenges. It presently relies on lab tests and other results done within NUHS, including tertiary hospitals and polyclinics. Results and data from other sources such as private general practitioners (GPs) or other hospitals, are not accessible. As a significant proportion of our patients also access healthcare from their own GPs and across healthcare clusters, this has the potential of missing important data sources. However, with the current HealthierSG transition and island-wide rollout of a common EMR system, we should soon have the means to overcome this limitation. Furthermore, Cardiosight by itself is purely a tool for surveillance (geographical, SES and other data traditionally not available to treating clinicians and population health experts). Without a complementary arm to help automate the delivery of interventions, there would be a large burden of work that would have to be undertaken by treating clinicians and regional health service teams to monitor data from CardioSight, to implement interventions for individual patients. Such labour-intensive strategies would be very hard to sustain. To mitigate this, CHAMP and other effector tools have been designed with the potential for seamless and automated linkup between the EHR, patient and treating clinicians. Cardiosight has the potential to help visualise and study disease and health patterns, and CHAMP to help integrate the patient's journey better and conveniently, reducing time required from the healthcare team. Despite the potential, all interventions targeting health-associated behaviours require individuals to embark on behavioural change to improve their cardiovascular health. Without the buy-in of the patients themselves, this exercise may all be in vain. Hence, this strategy has to be paired with the outreach efforts of HealthierSG, to improve heart health education and health literacy around this topic.

Healthcare delivery-preventive cardiology using CardioSight

Based on the burden at the geospatial level and individual risks, interventions are currently being designed to coordinate preventive cardiology care at a pilot stage within NUHS. These interventions represent the efferent arm of our CVD prevention efforts. Services will include digital interventions for the digitally native, and in-person coaching and other services for the digitally naive. These are aimed at optimising heart health through goal setting, addressing psychosocial health and willingness to change, optimising medical risk factors and cardioprotective medications. Most of these services have the potential to be delivered remotely, with a shared care model between primary care and specialists.

Interventions designed will target the main barriers to the implementation of healthy lifestyle practices, such as patient convenience and buy-in, together with tackling the heart of an integrative workflow between primary care practitioners and specialists.

Improved CVD prevention and mitigation, implementation using the CHronic diseAse Management Program (CHAMP)

Key components of CHAMP:

- CHAMP clinical decision support (CDS) system through the electronic medical record (EMR)

embedded and accessed through EPIC EMR that displays actionable items for clinicians to consider.
- WhatsApp chatbot specifically for patient interactions, patient engagement, and nudging utilising large language models.
- EndeavourAI software that analyses patient data and powers both the WhatsApp chatbot and CDS system.

CHAMP, an acronym for Chronic Disease Management Program, is an initiative that combines artificial intelligence with healthcare to manage prevalent conditions like diabetes, hypertension, and hyperlipidaemia. The program's central components are a patient-facing WhatsApp chatbot for communication and an AI-enhanced Clinical Decision Support (CDS) system for clinicians.

In the current clinical model outside the implementation of CHAMP, managing an increasing number of patients with chronic disease often means scaling up human resources, which could become unsustainable over time. Traditional home blood pressure monitoring (HBPM) and lifestyle counselling depend heavily on manual, in-person sessions. CHAMP's introduction aimed to streamline this process by automating patient reminders for HBPM and delivering lifestyle modifications advice via a chatbot, thus potentially improving patient compliance and health outcomes. This has potential for scaling as CHAMP is conceptually designed to not require additional healthcare manpower, therefore allowing an increasing number of patients to be cared for with the same number of healthcare providers.

CHAMP incorporates a clinician-facing CDS system whereby EMR-based recommendations are displayed for initiation of necessary medications based on risk and comorbidities, such as statins to target a specific LDL-C target and antihypertensives based on comorbidities, at the recommended dose. These clinical decision support items will later be further fine-tuned using machine learning algorithms and prioritised with training data optimising for reducing avoidable hospital visits. An AI-augmented software enables direct text-messaging with patients and transmission and integration of patient-triggered information, such as home blood pressure readings, into the smart AI-augmented EMR (Fig. 2 and Supplemental Fig. S2).

This integration and consolidation of data allows AI algorithms to generate patient specific actions or clinical decision support items for clinicians, thus completing the loop and displaying actions to the patient or the clinician. The implementation of such solutions holds the promise to offload primary care, enable seamless integration between the patient, PCP and specialist, and may improve effective care delivery while also enabling patient empowerment and involvement, and reducing healthcare burnout.

Like with CardioSight, EndeavourAI is the technological backbone of CHAMP, facilitating the integration of patient data from EMR into actionable insights without requiring active clinician input. This automation mirrors the principles of user-based collaborative filtering, which in CHAMP's context, would mean tailoring dietary recommendations based on patient-specific data and known health-positive diets, such as the Dietary Approaches to Stop Hypertension (DASH) diet for hypertension control.

There are existing limitations of CHAMP. As the pilot trial relies on a smartphone interface to liaise with patients, individuals who are digitally naive or do not own a smartphone may not be eligible. Hence, there would still need to be in-person interventions for this segment of individuals. The next concern is one of patient safety. As we look to trial direct AI-generated recommendations to patients, there is a need for careful oversight of the clinical team to ensure we first do no harm. Hence, direct patient messaging does not include AI-generated medication advice or titration and medication recommendations are directed to the clinical team for their consideration, ensuring clinical decision making is still in the hands of the clinician. However, this approach risks clinicians being inundated with clinical decision support prompts and not having proper oversight. This process has to be handled carefully.

There are key synergies of using CardioSight and CHAMP in combination for the delivery of CVD preventive care. CardioSight serves as a sophisticated tool designed to identify and stratify patients at risk for cardiovascular conditions. This forms the afferent arm for surveillance. However, identifying at-risk individuals is only the first step in a comprehensive care strategy. The real challenge lies in effectively reducing these risks and managing patient health proactively. CHAMP plays a crucial role as the effector arm for targeted intervention. By integrating with CardioSight's insights, CHAMP offers a targeted intervention strategy, engaging patients through personalised health management plans. Through its AI-driven components, such as the WhatsApp chatbot for patient communication and AI-enhanced Clinical Decision Support for healthcare providers, CHAMP acts on the insights provided by Cardiosight. Overall, this allows the identification of at-risk patients and implements actionable steps to mitigate their health risks, thereby closing the gap between risk identification and effective patient care management.

CHAMP is currently in beta trial and has served around 700 patients across different medical disciplines since the second half of 2023. Current challenges include ensuring operational viability by conforming and adapting to existing workflows for minimal change management, to help ensure long run sustained usage. We are currently in the phase of evaluating the effectiveness of its AI-driven components, including the impact on patient health management and clinician prescription patterns. The ongoing research will examine the empirical evidence of CHAMP's efficacy in a clinical setting with future plans for scaling and development of better personalisation methods. The development and deployment of CHAMP have been facilitated by the availability of comprehensive patient data and the collaborative effort of technology and healthcare experts to integrate AI into routine clinical practice.

Lessons learnt from development, testing and trial efforts

We currently have the vision and technological know-how to enable change, but the challenge of real-world execution depends particularly on people who are willing and able to proceed boldly in this endeavour. Our first lesson was to focus on good and constant communications between the multiple stakeholders, allowing data science professionals to have a common understanding with clinical professionals. For instance, the twin technologies of CardioSight and CHAMP were at different levels of maturity along their developmental lifecycle, comprising of 2 separate teams of engineers and clinicians. However, formal and informal sharing allowed for the identification of synergies and potential for integration. This eventually led to the use of CardioSight as the "affector" arm of risk identification and stratification, and use of CHAMP as a targeted "effector" arm to deliver interventions.

The second lesson is to adopt an agile working style, even while prioritising patient safety and data protection. With a project on this scale, mistakes and inefficiencies are likely the norm rather than the exception. However, even in the process of implementing novel solutions, we must ensure that we first do no harm. Hence steps are incorporated to prioritise safety during rapid cycles of development and deployment, such as frequent reviews of user access to the CardioSight and CHAMP platforms, strict clinical oversight with a graduated roll out process for new functionalities, and strict compliance to the Personal Data Protection Act (PDPA) in Singapore.

Lastly, we emphasise that coordination and collaboration with both local stakeholders and international experts is critical to developing the technological solutions and implementing them in the reduction of the population cardiovascular disease burden. Early collaboration and co-creation allow local leaders to contextualise these technologies to their health systems, and design solutions to bridge gaps between patients and the healthcare system. Collaboration with non-healthcare stakeholders also allows the exchange of best practices, to ensure that our systems are up to the standard of leading industry providers, while also broadening our horizons to future possibilities.

Next steps and future directions

Our first direction would be to streamline the clinical processes around the pilot framework between CardioSight as the affector and CHAMP as the effector arms of service delivery.

We are in the process of deeply studying population needs, inequity and trends in CVRFs, together with socioeconomic associations in the local population. This would identify populations of patients with suboptimal CVRF control and unmet care needs, and flag these to their local healthcare stakeholders such as GPs and polyclinics who are geographically close to the patients. Patients and primary care providers would next be invited to offer their opinions and co-create solutions using the platforms of CardioSight and CHAMP. Ultimately, we believe that a tripartite partnership between the platforms, patients and primary care providers would yield the most intuitive solutions for the local population.

Concurrently, we aim to improve the comprehensiveness of our data collection by integrating with data sources from local GPs and records from other hospitals and clusters in Singapore. This would involve checking the dataset for accuracy and comprehensiveness, while also ensuring data security and privacy during the integration process.

We aim to further refine AI-driven components so that CVRFs can be visualised more precisely, appropriate patients can be accurately and automatically flagged to their clinical teams with the recommended clinical actions, and patients can receive the most appropriate responses via the CHAMP platform. Large language models (LLM) and generative AI approaches would allow more refined prediction and clinical recommendations, based on better integration with clinical records of individual patients.

Lastly, we would share population data on cardiovascular health with the local clinical communities on a regular basis. This would help reveal the gaps of CVRF risk management to their local healthcare teams and encourage targeted solutions to improve overall population health over time. Furthermore, we would work to ensure appropriate consensus within the clinical community on aims of population-wide and targeted CVRF screening and optimisation of therapies. For instance, goals for LDL-C in different populations, and measurable outcomes for goal-directed medical therapy, such as appropriate statin therapy and others in the local context need to be clear.

Summary

In summary, trends in CVD prevalence and impact need to be addressed through improved population-wide and targeted approaches for CVD prevention in Singapore. Spurred on by the key enablers of a nationwide HealthierSG rollout and a switch to the capitation model of funding in our healthcare system, there is a pressing need for novel approaches to deliver CVD preventive care. At the same time, key challenges in the current provision of CVD prevention efforts must be addressed- improving health equity through better addressing social determinants of health, improved identification of individuals and groups currently under-treated, as well as effective and efficient outreach to individuals in community while offloading primary care. As a high-income country, Singapore has the advantages of an established health care system and plans for a national shared EMR. We also have developed health informatics tools to take advantage of AI solutions to address the main gaps in the provision of CVD prevention. The integration of novel technologies such as CardioSight and CHAMP into a CVD prevention approach at NUHS holds promise to enable the accurate identification of at-risk and under-treated groups, coupled with strategies to deliver targeted interventions in the community, thereby addressing some key gaps in CVD prevention. These strategies are currently being rolled out in various stages of development, with pilot testing to assess effectiveness and implementation before further scaling and integration into routine clinical processes.

Contributors
Mayank Dalakoti—conceptualisaion, writing, analysis, review; Scott Wong—analysis, review; Wayne Lee—writing, review; James Lee—analysis, review; Hayang Yang—writing, review; Shaun Loong—writing, review; Poay Huan Loh—review; Sara Tyebally—review; Andie Djohan—review; Jeanne Ong–review, James Yip—review; Kee Yuan Ngiam—review; Roger Foo—writing, review.

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Appendix A. Supplementary data
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