Patient Health Response in Emergent and Secure Habitats for Connected Healthcare

D.2.2 Clinical Pathway Analysis

Work package	WP2: Clinical Pathway Analysis
Type	Document
Date Due	31 May 2026
Date created	15 Feb 2024
Lead partner	Amsterdam UMC
Status	Submitted
Confidentiality	Public

Document history			
Version	**Date**	**Author**	**Description**
0.1	12/10	Jet Veltink	First publication
0.2	28/05	Jet Veltink, all partners	Document finalization

Document review		
Date	**Reviewer**	**Description**
05/27	HIGOE	Review finalization

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PHRESH

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1. Executive summary

1.1 Purpose, scope and key outcomes

For each use-case, clinical pathways are analysed and then modelled, which then allow for standardised treatmentand patient centric clinical decision making, regardless of the type of patients that are seen. These clinical pathway modelling by all the partners will be used to identify gaps, challenges for novel solutions and form a robust foundation for the proposed project.

1.2 Abbreviations

Abbreviations	**Definitions**
AECOPD	Acute exacerbation of chronic obstructive pulmonary disease
AI	Artificial Intelligence
COPD	chronic obstructive pulmonary disease
COVID-19	Coronavirus Disease 2019
CT	computed tomography
CVD	cardiovascular disease
ECG	electrocardiography
ED	Emergency Department
EEG	electroencephalogram
EHRs	electronic medical records
EMS	Emergency Medical Services
EU	European Union
GDPR	General Data Protection Regulation
HR	Heart Rate
IoMT	Internet of Medical Things
IoT	Internet of Things
KOLs	Key Opinion Leaders
Large language models	LLMs
LVO	large-vessel occlusion
ML	Machine learning
NHS	National Health Service
PET	privacy-enhancing technologies
PHRESH	Patient Health Response in Emergent and Secure Habitats for Connected Healthcare
PITL	Peers-In-The-Loop
RDHT	Remote Digital Health Technologies
RPM	remote patient monitoring
RR	respiratory rate
SBAR	Situation, Background, Assessment, Recommendation
SHAP	SHapley Additive exPlanations
SNS	Serviço Nacional de Saúde
SpO_2	oxygen saturation
UK	United Kingdom
WP	Work package
XAI	explainable AI

2. Introduction

The deliverable 2.2 Clinical Pathway Modelling Analysis provides a structured, roadmap for each PHRESH use-case by defining the clinical context, standardised practices & variations in interventions, and clinical decision-making. This deliverable presents a structured framework that serves as a foundation for PHRESH-technology development.

2.1 Background and context of the deliverable

The clinical pathway modelling analysis in the PHRESH project focuses on mapping patient care processes to support the integration of advanced remote health technologies. By reflecting real-world clinical pathways, it ensures that tools such as sensors, real-time data analytics, and quantum-secure encryption are aligned with patient needs. This modelling plays a key role in addressing health equity challenges, enabling secure data exchange, and meeting regulatory requirements. It also identifies opportunities for data collection and AI-driven analysis, helping the project deliver precise, effective healthcare solutions that improve care and outcomes.

2.2 Relation to the project objectives and work package

By mapping out clinical pathways in detail, WP2 ensures that the technical framework developed is highly relevant and tailored to real-world clinical practices. This pathway modelling helps identify the context, standardized practices & variation in interventions, and decision-making points data flows, which are essential for effective data collection in WP3 and accurate AI model development in WP4. Furthermore, a well-defined clinical pathway provides a structured approach to integrating security measures, which are developed in WP5, ensuring that patient data is handled appropriately throughout the process. Ultimately, the clinical pathway modelling in WP2 underpins the entire project, making sure that every step from data collection to integration aligns with clinical realities, facilitating a more seamless transition to the final demonstration in WP6.

3. Clinical pathway modelling analyses

3.1 The Netherlands – Connected Ambulance and Acute Care

3.1.1 Context

The Dutch acute care system is a critical, high-paced workflow characterized by multidisciplinary collaboration. Its performance depends on efficiency and comprehensive access to information in order to deliver high-quality care to critically ill patients. Despite this, the system operates under significant workload and stress and faces several key challenges:

- Suboptimal triage due to limited information availability
- Limited information exchange between ambulance services and receiving hospitals
- Inefficient resource allocation

The Joint Commission has identified inadequate communication and communication errors as frequent contributing factors to sentinel events (Alert, 2017; 'Joint Commission Center for Transforming Healthcare Releases Targeted Solutions Tool for Hand-off Communications', 2012; The Joint Commision, n.d.). Enhancing communication and information accessibility are therefore critical in improving patient outcomes and survival rates.

Within the acute care system limitations arise in prehospital information exchange, commonly called "handover", between diverse healthcare providers and the accessibility of critical information for diagnostics. This is particularly relevant for patients with potential acute large-vessel occlusion (LVO, a severe type of acute ischemic stroke where a major blood vessel supplying the brain is blocked), for whom timely treatment and direct transport to a specialized neurological intervention center are essential. Reduction in time-to-treatment is dependent on the availability of accurate prehospital information, which enables early initiation of the most effective clinical management strategy (Froehler et al., 2017).

3.1.2 Standardized practices and variation in interventions

In the acute care system, the information transfer process between emergency medical services (EMS) and the hospital comprises four sequential handovers:

- Pre-alert handover
- Pre-alert handover from STIP to Emergency Department (ED) nurse
- Team briefing
- Handover by EMS to ED team

Currently, each patient is registered at the ED through a brief telephone call between EMS personnel and the coordinating ED nurse. This so-called pre-alert handover is manually documented on a pre-alert form, providing a comprehensive summary of the patient's condition and constituting the first information handover.

The pre-alert form is subsequently transferred to an ED nurse (second handover), who then briefs the designated ED team using the pre-alert information, this step is referred to as the team briefing (third handover). Based on the information documented in the pre-alert form, the ED team initiates preparations for the patient's arrival. Upon arrival at the ED, EMS personnel deliver the final structured handover, regarding the patient's current clinical status using the SBAR (Situation, Background, Assessment, Recommendation) communication framework ('Richtlijn Gegevensuitwisseling acute zorg', n.d.).

In addition to standard patient data entry in the electronic patient record, documentation practices for handover information vary between hospitals. During the handover, information is often recorded manually by the ED team on a whiteboard or in a notebook.

Figure 1 presents a general clinical pathway of an acute care patient in the Netherlands by making use of metro-mapping. Four sequential phases are depicted in the vertical columns and disguised by the colours: blue, green, red and yellow.

1) the emergency-onset phase (blue)
2) the ambulance-activation phase (green)
3) prehospital patient-arrival phase (red):

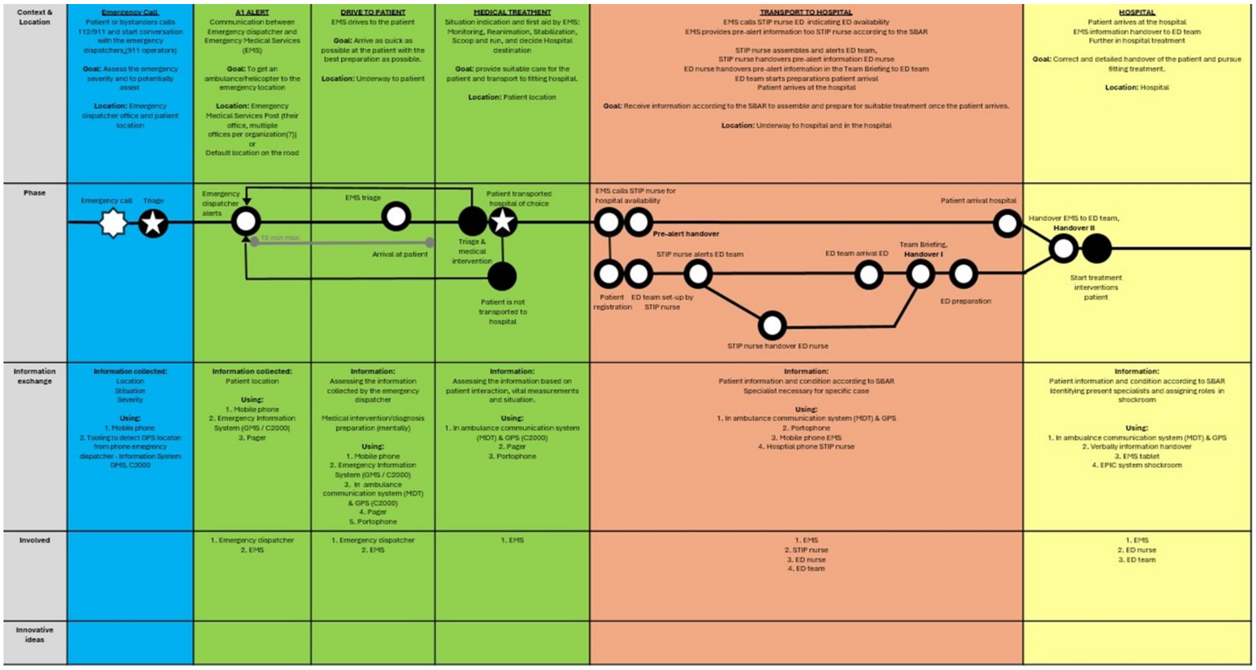
- Pre-alert handover
- Pre-alert handover from STIP (the coordinating ED nurse) to ED nurse
- Team briefing

4) posthospital patient-arrival phase (yellow):

- Handover by EMS to ED team

Within each phase, each row displays the following information: context & location, phase, information exchanged, healthcare professionals involved, and innovative concepts. Each bullet point denotes a decision point (star), an intervention (bullet point black) or the transfer of information (black/white bullet point).

Figure 1: Dutch Acute Care Patient Journey through Metro Mapping



For the original picture, please see the attached PowerPoint file.

3.1.3 Clinical decision making

Based on prehospital information, the ED team initiates preparatory actions and, where necessary, notifies relevant specialists. However, the ED does not receive real-time updates on the patient's condition during transport, effectively rendering the ambulance a "black box" in the information flow. In cases where the patient deteriorates en route to the hospital, the ED is not consistently informed, which may result in delays in team escalation or necessary adjustments to the treatment approach upon patient arrival.

In suspected LVO patients, the standard clinical pathway typically involves initial transport to a primary stroke center, where a computed tomography (CT) scan is performed to confirm the diagnosis and assess eligibility for treatment. Upon identification of an LVO, the patient is subsequently referred for transfer to a comprehensive stroke center to undergo endovascular thrombectomy. However, this "drip-and-ship" model introduces considerable time delays, as it encompasses multiple steps; imaging, clinical decision-making, and inter-hospital transfer, which collectively prolongs the time to treatment. Existing literature indicates that the time spent at the initial hospital, including delays between CT acquisition and the transfer request, constitutes a significant portion of the overall treatment time. This is of particular concern given the strong time-dependency of thrombectomy efficacy, with outcomes deteriorating as treatment is delayed. Strategies to enhance the availability of diagnostic information for earlier identification of LVO could optimize prehospital triage protocols, facilitating direct transport to comprehensive stroke centers.

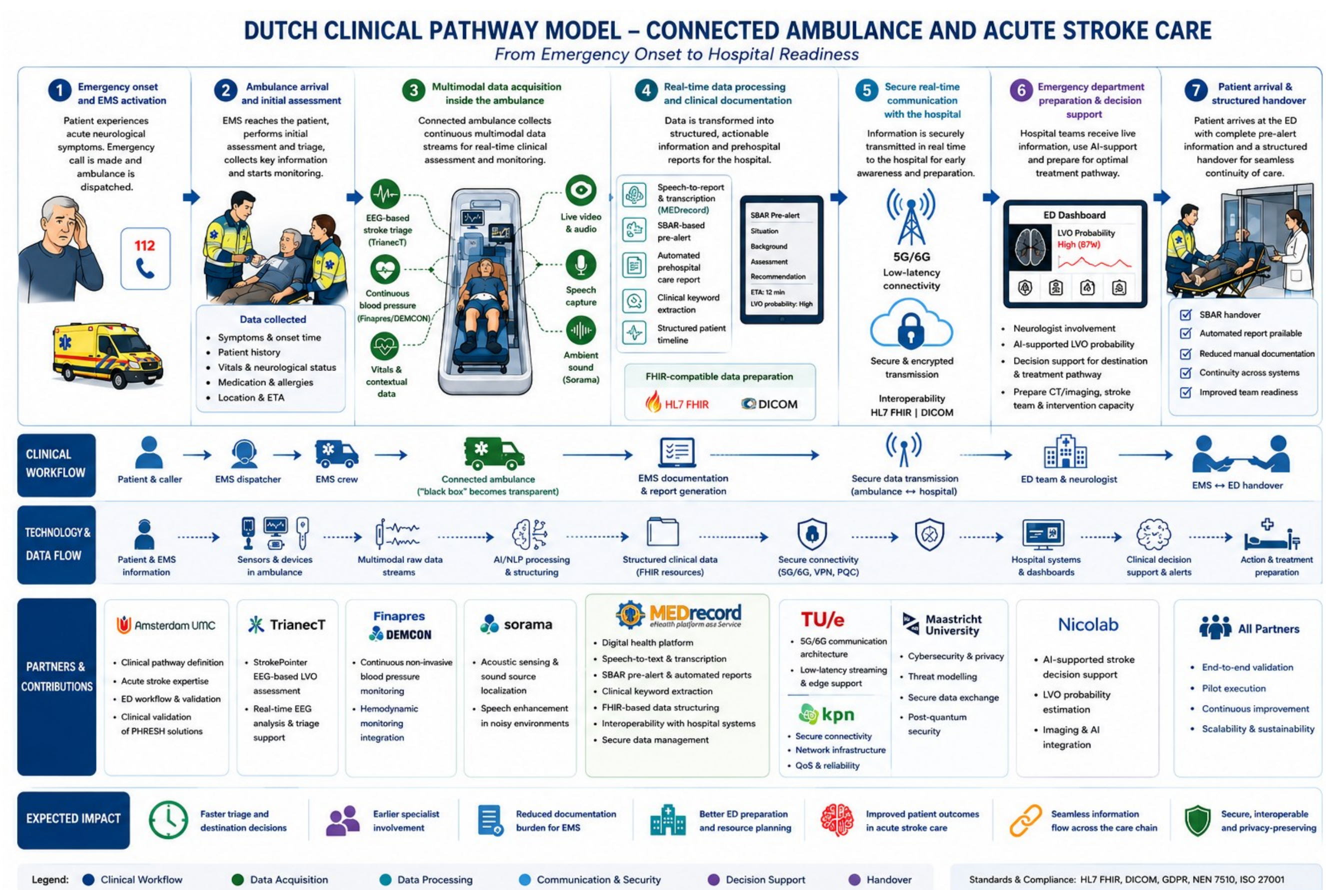
Such approaches may mitigate treatment delays and ultimately improve clinical outcomes (Froehler et al., 2017; van Meenen et al., 2021)

The PHRESH framework aims to address these limitations by enabling real-time multimodal data sharing and AI-assisted triage support during ambulance transport. By integrating EEG, continuous blood pressure monitoring, speech recognition, and live audiovisual communication, PHRESH supports earlier neurological assessment and more informed destination decisions, potentially reducing time-to-treatment and improving patient outcomes in acute stroke care.

3.1.4 Clinical Pathway model

The aim of the proposed clinical pathway model is to realize a secure and real-time patient data exchange between the ambulance and hospitals enabling data-driven solutions to improve healthcare efficiency.

The connected ambulance is the fundamental basis of the model in which all patient data is collected by smart vital parameter devices and used for efficient LVO triage. Electrical brain activity can be measured and automatically analysed by StrokePointer system developed by TrianecT, providing a LVO likelihood score for quantitative triage decision support. Wireless continuous blood pressure monitoring will be enabled by Finapres or Demcon. In addition, together with Strokeviewer of Nicolab the patient data will be integrated for AI-based analysis tool for treatment. Sorama facilitates the localization and identification of sound sources within the ambulance environment. Additionally, Medrecord will develop a speech-to-report system that documents communication between EMS personnel and patients, which can be employed to obtain supplementary patient history and monitor changes in patient condition. The real-time data is exchanged utilizing live video between ambulance and hospital through 5G/6G data communication architecture developed by Eindhoven University of Technology. Maastricht university and KPN secure the connectivity and cybersecurity.



3.1.5 Challenges and novel solutions specification

Communication challenges within the Dutch acute care system persist in multiple sequential information transfers, combined with the limited transparency of real-time patient conditions within the ambulance (often described as a "black box"), reducing overall patient care efficiency.

Furthermore, the lack of critical prehospital information complicates triage processes and contributes to delays in the initiation of treatment or choice for neurological specialisation hospital in case of potential LVO.

The challenges encountered within the Dutch acute care system can be addressed through the integration of the following novel solutions:

- **Real-time patient monitoring and diagnostic support:** implementing EEG and continuous blood pressure monitoring systems within the dynamic system between ambulance and ED.
- **AI-based triage support:** prehospital LVO identification through AI-based triage support combining vital parameters, patient history and live video/audio connection.
- **Seamless, secure and encrypted communication channels through livestream ambulance connection between EMS and ED:** data transfer through 5G/6G networks.
- **Automated clinical documentation and speech-to-report integration**: deployment of speech recognition technologies capable of operating within noisy ambulance environments to automatically generate structured SBAR-based prehospital reports integrated into hospital workflows.

3.2 Canada – Remote Cardiovascular Monitoring

3.2.1 Context

The Canadian use-case focuses on remote cardiovascular disease (CVD) monitoring and management, with a strong emphasis on improving health equity for rural and underserved populations. In Canada, approximately 18% of the population living in remote or rural areas, while only a small proportion of specialists are available in these regions. This imbalance limits access to timely diagnosis, continuous monitoring, and specialist-driven decision-making.

CVD remains a major public health issue, accounting for a significant proportion of mortality, yet a large share of cases is preventable through early detection and continuous monitoring. The Canadian contribution in PHRESH addresses these challenges by leveraging remote patient monitoring (RPM), wearable and contactless sensors, and AI-driven analytics to enable early intervention and prevention strategies.

The ecosystem is built around a distributed care model where patients are monitored in their homes or communities, data is collected continuously, and clinical insights are generated remotely. This model is supported by a strong focus on privacy, security, and regulatory compliance (e.g., PIPEDA), reflecting the Canadian healthcare environment and its constraints on data sharing.

3.2.2 Standardized practices and variation in interventions

Clinical practice in Canada for CVD management generally follows standardized guidelines for risk assessment, monitoring of vital signs, and intervention thresholds (e.g., blood pressure, heart rate, oxygen saturation). Increasingly, these practices are being extended beyond clinical facilities into home monitoring and telehealth settings, supported by wearable devices and digital health platforms.

However, there is considerable variation in how interventions are implemented due to:

- Geographic disparities (urban vs. remote care access),
- Availability of monitoring technologies,
- Integration of telehealth services across provinces.

Within the PHRESH framework, the Canadian pathway builds on a standardized monitoring layer, combined with personalized intervention strategies:

- Preventative interventions (lifestyle recommendations, alerts),
- Clinical interventions (remote physician consultation, medication adjustments),
- Emergency interventions (automated alerts to dispatch services and hospitals).

The integration of multi-parametric sensors and AI-based analysis allows for a more consistent application of clinical guidelines while enabling context-aware adaptation based on patient-specific conditions and environments.

3.2.3 Clinical decision making

Clinical decision-making in the Canadian use case is data-driven and augmented by AI models, combining continuous monitoring data with predictive analytics and clinical expertise.

The decision process follows three main stages:

1. Data acquisition and preprocessing
   Continuous streams of physiological data are collected via wearable and contactless sensors (e.g., heart rate, blood pressure, respiration, oxygen saturation). These are aggregated on a secure platform for analysis.
2. Risk assessment and prediction
   AI/ML models generate individual risk profiles, detect anomalies, and predict potential adverse events (e.g., cardiac events). These models leverage both real patient data and synthetic data augmentation to improve robustness and generalization.
3. Decision support and action triggering
   The system provides preventative alerts to patients, clinical decision support for healthcare providers, emergency alerts to response teams when critical thresholds are exceeded.

A key characteristic of the Canadian approach is the integration of privacy-preserving collaborative learning and explainable AI (XAI), enabling clinicians to understand and trust AI outputs while maintaining compliance with strict privacy regulations.

3.2.4 Clinical Pathway model

The Canadian clinical pathway can be summarized as a continuous and connected loop, structured around three core phases:

1. Sense and collect

Patients are continuously monitored using wearable and contactless sensors, including advanced devices capable of measuring multiple CVD-related parameters in real-time. Data is transmitted securely to a centralized or distributed platform.

2. Analyze and alert

Collected data is processed using AI models to generate personalized risk scores, detect deviations from normal patterns, and trigger alerts (preventative or emergency).

3. Intervene and coordinate care

Depending on the detected risk level:

- Low risk: patient receives guidance (e.g., lifestyle recommendations),
- Medium risk: remote clinician intervention is triggered,
- High risk: emergency services are alerted, with real-time data shared to support triage and treatment.

This pathway can be further enhanced by connecting with other contributions from the consortium: integration with ambulance and hospital systems for continuity of care, hybrid data models (real + synthetic) for improved prediction, secure data sharing mechanisms to ensure compliance and interoperability.

The pathway supports both chronic disease management and acute event response, bridging the gap between home monitoring and emergency care.

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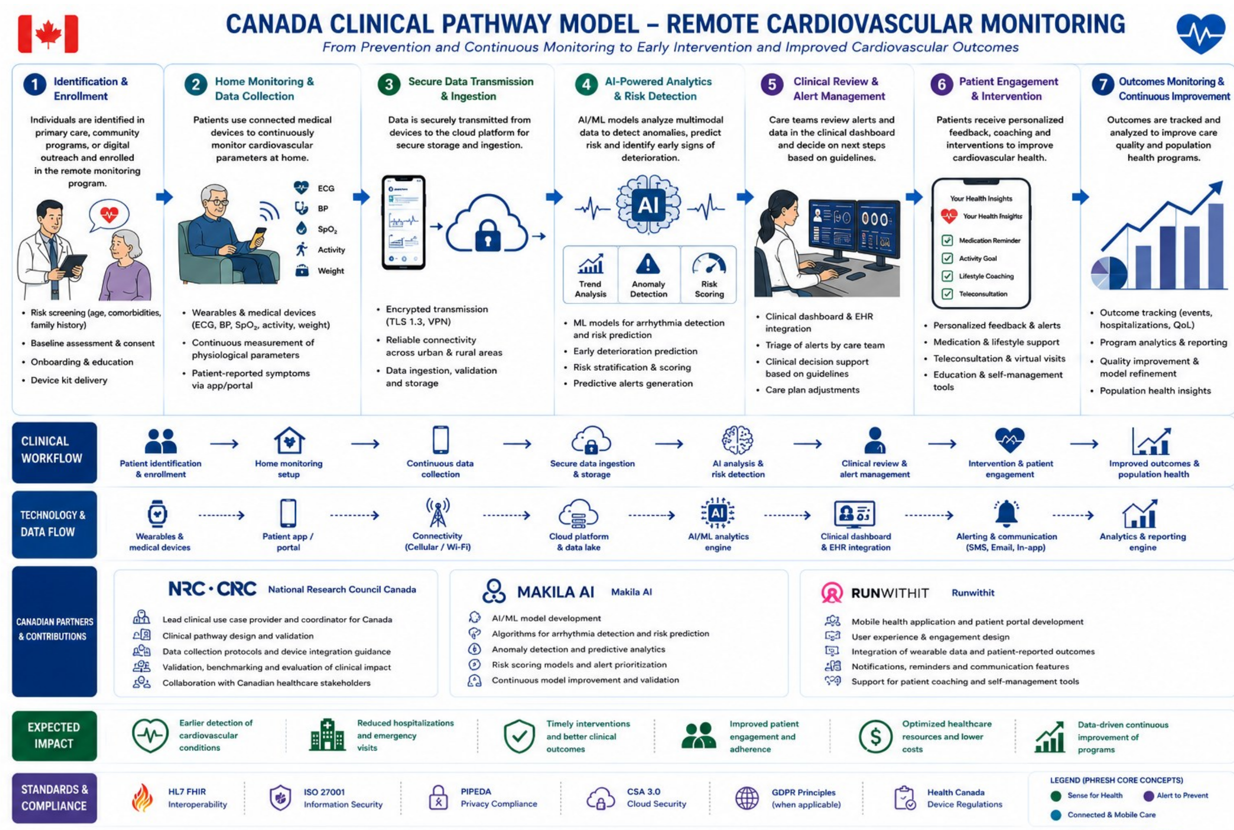

3.2.5 Challenges and novel solutions specification

The Canadian use case faces several key challenges:

1. Connectivity and access

Remote regions often suffer from limited connectivity, impacting real-time monitoring and response. Solution: use of edge computing and next-generation networks (5G/6G) to enable low-latency, reliable data transmission.

2. Data privacy and regulatory constraints

Strict privacy laws limit data sharing and collaboration across institutions.

Solution: deployment of privacy-enhancing technologies (PET) such as federated learning, homomorphic encryption, and post-quantum cryptography to ensure secure data usage without compromising privacy.

3. Data fragmentation and interoperability

Healthcare data is often siloed across systems.

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Solution: a unified, modular platform supporting standardized data exchange and integration of heterogeneous devices and systems.

4. Accuracy and reliability of monitoring systems

Wearable devices may lack clinical-grade accuracy or robustness.

Solution: development of multi-sensor systems and sensor fusion techniques, combined with AI for noise reduction and improved reliability, ensuring that the impact of potential shortcomings of the devices themselves is minimized in the encompassing integrated system.

5. Adoption and trust

Patient and clinician trust is essential for widespread adoption of digital health solutions.

Solution: incorporation of explainable AI, transparent data usage policies, and secure infrastructure to build trust.

3.3 Portugal – Domiciliary and Home Care

3.3.1 Context

The COVID-19 pandemic exposed structural limitations in hospital-centric healthcare systems, leading to significant hospital overload and reduced capacity to manage both acute and chronic patients. In Portugal, this situation intensified the need for safe, effective, and scalable home-based care alternatives, capable of ensuring continuity of care while alleviating pressure on hospital units.

Domiciliary healthcare has become a strategic response to these challenges; however, its effectiveness is currently limited by insufficient remote monitoring capabilities, fragmented information flows, and inefficient coordination between home care teams and hospitals. These limitations affect not only healthcare professionals but also the coordinating hospitals, which lack real-time visibility over patient conditions and team operations. Addressing these gaps requires the adoption of digital, integrated, and secure solutions that enable continuous monitoring, intelligent data analysis, and coordinated clinical and operational decision-making.

3.3.2 Standardized practices and variation in interventions

Current domiciliary care practices vary significantly across teams, regions, and institutions, often relying on manual procedures, non-standardized reporting, and heterogeneous intervention criteria. This variability leads to inconsistencies in care delivery, delayed responses, and increased risk of human error.

The proposed solution promotes the standardization of domiciliary care practices through continuous, sensor-based patient monitoring and centralized digital platforms. By providing uniform access to real-time clinical and operational data, the system supports consistent intervention protocols while still allowing flexibility to adapt care plans to individual patient needs. This balance between standardization and personalization ensures higher quality of care, improved traceability of interventions, and better alignment between home care teams and hospital guidelines.

3.3.3 Clinical decision making

Clinical decision making in domiciliary care is currently constrained by limited and episodic patient data, often collected during scheduled visits or reported manually. This reactive approach reduces the ability to detect early clinical deterioration and to intervene preventively.

The proposed approach enables data-driven clinical decision making by continuously collecting vital and contextual health data through wearables and multiparameter sensors deployed in patients' homes. These data are intelligently analyzed using AI-driven tools, generating informative, preventive, and emergency alerts. Healthcare professionals receive timely, actionable insights that support early intervention, prioritization of cases, and more accurate clinical assessments, ultimately improving patient safety and outcomes.

3.3.4 Clinical Pathway model

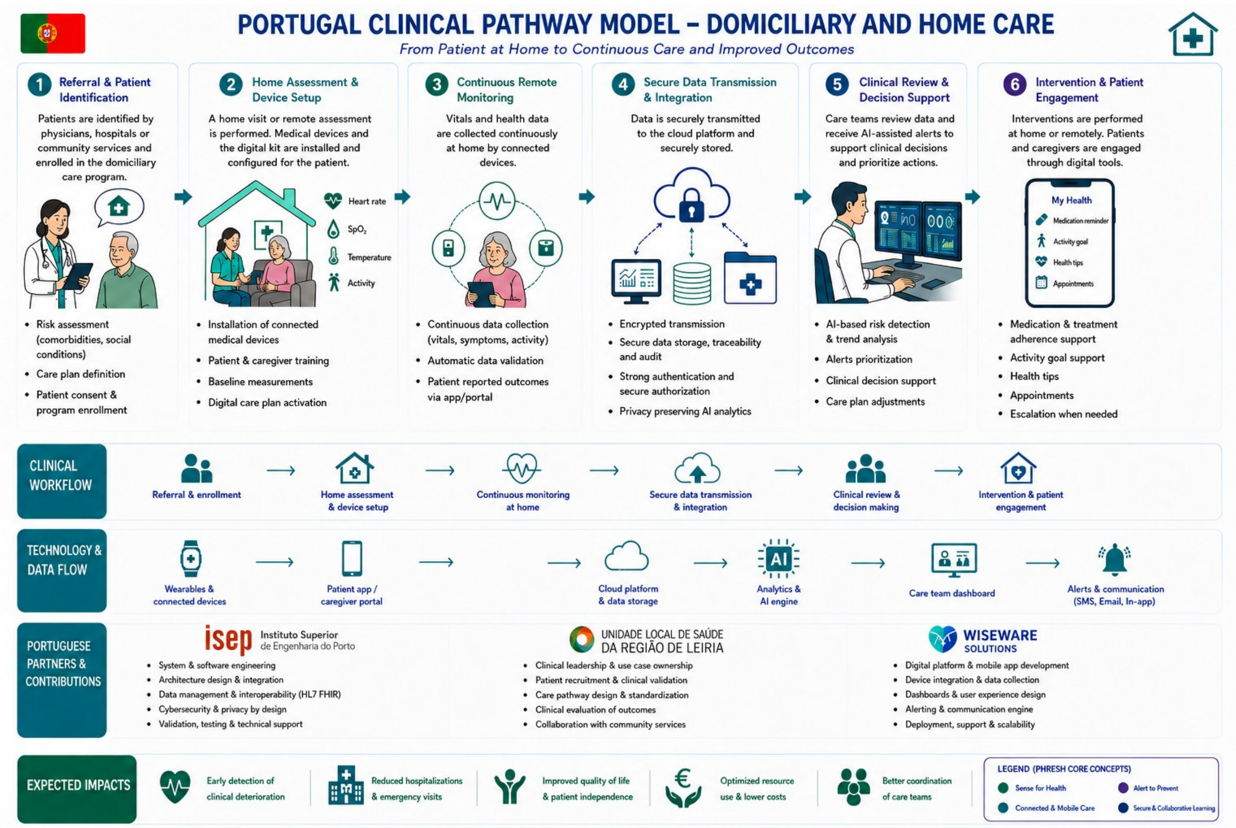
The proposed clinical pathway model represents a paradigm shift from episodic, hospital-centered care to a continuous, digitally enabled home–hospital care model. It is designed to support patients undergoing domiciliary treatment while maintaining strong clinical oversight by coordinating hospitals.

At the core of this model is the continuous acquisition of clinical and contextual data through wearables and multiparameter sensors installed in patients' homes. These devices collect vital signs and relevant physiological parameters, enabling real-time monitoring of patient health status beyond scheduled visits. Data are securely transmitted to a centralized digital platform, ensuring availability to authorized healthcare professionals across different roles and shifts.

The platform acts as a single point of coordination, integrating clinical monitoring, care planning, logistics, and communication. AI-driven analytics process incoming data to identify trends, deviations, and potential risks, triggering informative, preventive, or emergency alerts. These alerts guide clinical decision-making, support early intervention, and help prioritize patients based on clinical urgency.

The pathway also incorporates operational support mechanisms that align clinical needs with resource management. Medication and medical equipment requirements are anticipated based on patient status and treatment plans, while route optimization tools improve the efficiency of home visits. Automated daily reporting ensures consistent documentation, reduces administrative burden, and enhances traceability of clinical actions.

Communication within the pathway is structured and bidirectional, allowing seamless interaction between home care teams, back-office staff, caregivers, and hospital specialists. This ensures continuity of care across shifts and reduces information loss or duplication. The possible integration with the national healthcare system (SNS) guarantees interoperability with existing clinical records and workflows, enabling scalability and long-term adoption.


PORTUGAL CLINICAL PATHWAY MODEL – DOMICILIARY AND HOME CARE
From Patient at Home to Continuous Care and Improved Outcomes
1 Referral & Patient Identification
Patients are identified by physicians, hospitals or community services and enrolled in the domiciliary care program.
• Risk assessment (comorbidities, social conditions)
• Care plan definition
• Patient consent & program enrollment
2 Home Assessment & Device Setup
A home visit or remote assessment is performed. Medical devices and the digital kit are installed and configured for the patient.
Heart rate
SpO₂
Temperature
Activity
• Installation of connected medical devices
• Patient & caregiver training
• Baseline measurements
• Digital care plan activation
3 Continuous Remote Monitoring
Vitals and health data are collected continuously at home by connected devices.
• Continuous data collection (vitals, symptoms, activity)
• Automatic data validation
• Patient reported outcomes via app/portal
4 Secure Data Transmission & Integration
Data is securely transmitted to the cloud platform and securely stored.
• Encrypted transmission
• Secure data storage, traceability and audit
• Strong authentication and secure authorization
• Privacy preserving AI analytics
5 Clinical Review & Decision Support
Care teams review data and receive AI-assisted alerts to support clinical decisions and prioritize actions.
• AI-based risk detection & trend analysis
• Alerts prioritization
• Clinical decision support
• Care plan adjustments
6 Intervention & Patient Engagement
Interventions are performed at home or remotely. Patients and caregivers are engaged through digital tools.
My Health
Medication reminder
Activity goal
Health tips
Appointments
• Medication & treatment adherence support
• Activity goal support
• Health tips
• Appointments
• Escalation when needed
CLINICAL WORKFLOW
Referral & enrollment
Home assessment & device setup
Continuous monitoring at home
Secure data transmission & integration
Clinical review & decision making
Intervention & patient engagement
TECHNOLOGY & DATA FLOW
Wearables & connected devices
Patient app / caregiver portal
Cloud platform & data storage
Analytics & AI engine
Care team dashboard
Alerts & communication (SMS, Email, In-app)
PORTUGUESE PARTNERS & CONTRIBUTIONS
isep Instituto Superior de Engenharia do Porto
• System & software engineering
• Architecture design & integration
• Data management & interoperability (HL7 FHIR)
• Cybersecurity & privacy by design
• Validation, testing & technical support
UNIDADE LOCAL DE SAÚDE DA REGIÃO DE LEIRIA
• Clinical leadership & use case ownership
• Patient recruitment & clinical validation
• Care pathway design & standardization
• Clinical evaluation of outcomes
• Collaboration with community services
WISEWARE SOLUTIONS
• Digital platform & mobile app development
• Device integration & data collection
• Dashboards & user experience design
• Alerting & communication engine
• Deployment, support & scalability
EXPECTED IMPACTS
Early detection of clinical deterioration
Reduced hospitalizations & emergency visits
Improved quality of life & patient independence
Optimized resource use & lower costs
Better coordination of care teams
LEGEND (PHRESH CORE CONCEPTS)
Sense for Health
Alert to Prevent
Connected & Mobile Care
Secure & Collaborative Learning

3.3.5 Challenges and novel solutions specification

Domiciliary healthcare faces multiple challenges, including the inability to continuously monitor patients at distance, inefficient logistics and resource planning, fragmented communication, and increased administrative burden on both care teams and hospitals. These challenges are further compounded by strict requirements for data privacy, security, and regulatory compliance.

The proposed solution addresses these challenges through novel and integrated approaches, including:

- Deployment of wearables and multiparameter sensors for continuous home monitoring.
- AI-based analysis and multi-source data fusion to generate accurate and contextual alerts.
- Privacy- and security-by-design mechanisms that allow intelligent systems to use health data without disclosing sensitive information.
- Automated workflows for reporting, alerts, and operational planning, reducing manual tasks and errors.
- Integration with the national healthcare system (SNS) to ensure alignment with existing clinical infrastructures.

Together, these innovations enable a scalable, secure, and efficient domiciliary care model that frees hospital capacity for intensive care, improves response times for home interventions, and fully digitizes the home–hospital workflow.

3.4 Romania – Cardiovascular and Cerebrovascular Monitoring

3.4.1 Context

Cardiovascular and cerebrovascular diseases remain among the leading causes of mortality and long-term disability worldwide, representing a major burden for healthcare systems and society. Romania continues to experience one of the highest cardiovascular mortality rates in Europe, with hypertension, ischemic heart disease, stroke, diabetes, obesity, smoking, and population aging contributing significantly to the increasing prevalence of chronic cardiovascular conditions. Rural and underserved regions are particularly affected by limited access to healthcare services, shortage of medical personnel, delayed diagnosis, and reduced availability of specialized cardiovascular care. Studies analysing healthcare accessibility in Romania emphasize the important disparities between urban and rural healthcare infrastructures, especially regarding access to cardiology services and emergency care (Cioclu et al.,2024).

The Romanian PHRESH use case focuses on improving primary healthcare accessibility and remote cardiovascular monitoring in the Apuseni mountain region (Țara Moților – Țara de Piatră), a geographically isolated and predominantly rural area spanning portions of Alba, Arad, Bihor, Cluj, and Hunedoara counties. The region covers approximately 7,471 square kilometres and includes numerous small villages and remote communities with difficult geographical access and limited healthcare infrastructure. The local population is characterized by a relatively high proportion of elderly individuals, patients with chronic diseases, and vulnerable populations requiring long-term healthcare supervision and continuity of care.

One of the major healthcare challenges in the Apuseni region is the shortage of family doctors and healthcare professionals in rural and mountainous communities. Several villages lack permanent healthcare providers, while existing family doctors may serve very large and geographically dispersed populations. In certain localities, a single physician may provide care for between 800 and 6000 residents, while after-hours healthcare centres and emergency support infrastructures remain insufficiently developed. Transportation difficulties, mountainous terrain, and long travel distances may significantly delay access to diagnostics, treatment, and emergency intervention, especially for elderly or mobility-impaired patients.

Improving primary healthcare access and continuity of care in rural regions has therefore become an important strategic priority both for Romanian healthcare authorities and for local regional development initiatives. The Association for the Development of the Microregion Moții, Țara de Piatră aims to support sustainable regional development, including healthcare accessibility, public health services, and digital transformation initiatives capable of improving quality of life in remote communities. Within this context, remote digital health technologies are increasingly considered promising solutions for overcoming geographical and socioeconomic barriers affecting healthcare delivery in isolated areas.

Remote Digital Health Technologies (RDHT), wearable sensing systems, and telemonitoring infrastructures may provide more accessible, cost-effective, and continuous healthcare support for patients living in rural and underserved environments. Continuous monitoring of physiological parameters such as blood pressure, heart rate, oxygen saturation, physical activity, and sleep patterns may support earlier identification of cardiovascular deterioration and facilitate preventive intervention strategies. Recent studies demonstrate that wearable monitoring technologies and remote patient monitoring systems can improve chronic cardiovascular disease management, support continuity of care, and reduce avoidable hospitalizations by enabling earlier detection of physiological abnormalities outside traditional clinical settings.

The Romanian PHRESH use case proposes a conceptual and exploratory deployment scenario focused on remote cardiovascular monitoring for elderly and at-risk populations in the Apuseni region through the integration of wearable technologies, secure IoMT communication infrastructures, and AI-assisted monitoring mechanisms. As the Romanian consortium currently does not include an active clinical deployment partner, the proposed use case is intended to illustrate a theoretical pathway model demonstrating how continuous non-invasive blood pressure monitoring, wearable sensing technologies, and intelligent alerting systems could support primary healthcare services and remote patient supervision in underserved regions.

The envisioned PHRESH approach combines sensor data acquisition, real-time telemetry, wearable monitoring devices, cloud-based communication infrastructures, and machine learning models for early detection of potential cardiovascular risk situations. Continuous physiological monitoring and AI-assisted analysis may support earlier identification of abnormal trends and facilitate timely communication between patients, caregivers, healthcare professionals, and emergency response services. The proposed approach also aligns with broader PHRESH objectives related to connected healthcare ecosystems, preventive care, secure interoperability, and digital health accessibility for vulnerable populations.

Within this framework, BEIA Consult International contributes as a system integrator and IoT solution provider, leveraging its expertise in IoMT telemetry, cloud communication systems, wearable integration, secure data transmission, and remote monitoring infrastructures. BEIA has extensive experience in telemonitoring platforms, sensor integration, emergency communication systems, and distributed IoT architectures through participation in numerous European and national research and innovation projects. The company also collaborates with a broad healthcare ecosystem including hospitals, clinics, elderly homes, home care providers, pharmacies, and healthcare-related organizations, supporting future scalability and integration opportunities for connected healthcare services.

The Romanian use case therefore illustrates how secure and scalable remote monitoring infrastructures may contribute to improving healthcare accessibility, continuity of care, and early cardiovascular risk detection for isolated and underserved populations living in rural mountainous regions.

3.4.2 Standardized practices and variation in interventions

In Romania, the management of cardiovascular and cerebrovascular conditions is predominantly based on traditional healthcare workflows centred around in-person consultations, episodic physiological measurements, and hospital-based interventions. Patients experiencing symptoms such as hypertension-related complications, chest pain, arrhythmias, dizziness, fatigue, or neurological manifestations commonly seek medical assistance through family doctors, outpatient clinics, emergency departments, or regional hospitals depending on symptom severity and healthcare accessibility.

The standard clinical pathway generally involves intermittent measurements of blood pressure, heart rate, electrocardiography (ECG), oxygen saturation, and laboratory investigations obtained during scheduled consultations or emergency presentations. Clinical decision-making relies heavily on physician observation, patient self-reporting, and manually interpreted measurements collected at isolated time points. Follow-up procedures are often episodic and dependent on physical attendance at healthcare facilities, especially for elderly patients and individuals with chronic cardiovascular conditions.

Although this approach remains the standard practice in many healthcare environments, it presents important limitations regarding continuous monitoring and early identification of physiological deterioration. Cardiovascular and cerebrovascular conditions frequently evolve progressively over time, while physiological abnormalities occurring between consultations may remain undetected until acute decompensation or emergency hospitalization becomes necessary. Studies investigating digital cardiovascular monitoring indicate that intermittent assessments may fail to capture transient physiological changes and dynamic cardiovascular variability occurring outside clinical environments (Berkebile et al., 2025).

The Romanian healthcare system also faces important challenges related to fragmented patient information and limited interoperability between healthcare providers, emergency services, and monitoring infrastructures. Patient data are often distributed across isolated healthcare systems, reducing continuity of care and limiting real-time access to longitudinal physiological information. In many situations, healthcare professionals rely on incomplete patient histories or delayed information exchange, potentially affecting preventive intervention and emergency response efficiency.

These limitations are particularly evident in rural and mountainous regions such as the Apuseni area, where healthcare accessibility remains significantly constrained by geographical isolation, shortages of healthcare professionals, and transportation difficulties. Urban healthcare centres generally benefit from better-equipped hospitals, specialized cardiology services, advanced diagnostic infrastructures, and improved emergency response capabilities. In contrast, rural and remote communities frequently experience reduced access to specialists, limited diagnostic facilities, insufficient after-hours healthcare centres, and longer travel times to healthcare institutions.

The Apuseni region illustrates these disparities clearly. Several villages lack permanent healthcare providers, while existing family doctors may cover geographically dispersed populations across multiple remote settlements. Delays in transportation and difficult access to specialized healthcare services may contribute to delayed diagnosis and treatment of cardiovascular emergencies. Elderly populations and patients with chronic diseases are particularly vulnerable to these healthcare accessibility limitations. Research focused on healthcare inequalities in Romania and Eastern Europe highlights that geographical accessibility remains a major determinant of healthcare continuity and patient outcomes (Cioclu et al., 2024).

Variation in intervention pathways also arises from differences in digitalization maturity and healthcare infrastructure capabilities between healthcare providers. While certain urban hospitals and clinics have partially implemented telemedicine services and electronic health infrastructures, many rural healthcare settings still rely predominantly on conventional workflows with limited remote monitoring or interoperability capabilities. Consequently, continuity between home-based care, ambulatory monitoring, emergency response, and hospital admission remains insufficiently integrated.

Pre-hospital emergency care presents additional operational challenges relevant to the PHRESH use case. Ambulance teams often have limited access to patient longitudinal monitoring data or real-time physiological information before arriving at the scene. Communication between emergency teams and hospitals may rely primarily on verbal reporting and basic triage information, limiting the ability of healthcare providers to prepare interventions in advance. Furthermore, telemetry capabilities during patient transport remain limited in many situations, reducing continuity of monitoring between home environments and emergency healthcare settings.

Within the PHRESH Romanian use case, these limitations are addressed through a conceptual framework integrating wearable sensing technologies, secure IoMT communication infrastructures, remote telemetry platforms, and AI-assisted monitoring mechanisms. The proposed approach aims to support continuous physiological observation and improve continuity between home-based monitoring, primary healthcare, and emergency response services.

The envisioned pathway introduces wearable monitoring devices capable of continuously collecting cardiovascular parameters such as blood pressure, heart rate, oxygen saturation, and activity levels. Physiological data may be securely transmitted through cloud-based IoMT communication infrastructures, enabling remote supervision and longitudinal monitoring of at-risk patients living in geographically isolated regions.

AI-assisted analytics and intelligent alerting mechanisms may support earlier identification of abnormal physiological trends and facilitate more proactive interventions for elderly and vulnerable populations. The PHRESH approach also aims to improve coordination between patients, caregivers, healthcare professionals, and emergency services by enabling continuous telemetry and remote access to patient physiological information.

As the Romanian use case currently represents a theoretical and exploratory deployment scenario without an active clinical deployment partner, the proposed intervention pathway is intended primarily to illustrate how connected healthcare technologies, wearable systems, and secure telemetry infrastructures could support healthcare accessibility and preventive cardiovascular monitoring in underserved rural regions.

BEIA contributes to this conceptual framework through expertise in IoMT telemetry, telemonitoring platforms, secure communication systems, cloud-based infrastructures, and remote sensing integration. The company supports the envisioned digital infrastructure enabling continuous monitoring, wearable connectivity, secure data transmission, and scalable remote healthcare communication adapted to distributed rural environments.

3.4.3 Clinical decision making

Clinical decision making in cardiovascular and cerebrovascular healthcare is traditionally based on episodic clinical assessments, physician expertise, patient self-reporting, and intermittent physiological measurements collected during consultations or hospital admissions. In Romania, as in many healthcare systems, healthcare professionals typically evaluate cardiovascular risk and disease progression using blood pressure measurements, electrocardiography (ECG), oxygen saturation, laboratory investigations, imaging results, and patient medical history obtained during scheduled visits or emergency presentations.

Although these conventional approaches remain clinically essential, they present several limitations for long-term monitoring and preventive healthcare management. Cardiovascular deterioration frequently develops progressively over time, while physiological changes occurring between consultations may remain unnoticed until severe symptoms or acute events emerge. In many situations, clinical decisions are therefore reactive rather than preventive, relying on measurements captured only after significant deterioration has already occurred. Studies in digital cardiovascular medicine highlight that continuous monitoring and longitudinal physiological observation may improve early detection of cardiovascular anomalies and support more proactive clinical management strategies (Sultana et al., 2025).

In rural and geographically isolated regions such as the Apuseni mountain area, clinical decision making is additionally affected by limited healthcare accessibility, shortages of family doctors, transportation barriers, and delayed access to specialist consultations. Healthcare professionals serving remote communities often face difficulties in ensuring continuous follow-up for elderly and chronically ill patients, particularly when monitoring depends exclusively on physical consultations and patient-initiated visits. Consequently, early physiological deterioration or worsening chronic conditions may remain undetected for extended periods.

The Romanian PHRESH use case proposes a conceptual remote monitoring framework designed to support preventive healthcare and improve continuity of care through continuous physiological monitoring, secure telemetry infrastructures, and AI-assisted analysis mechanisms. The envisioned approach focuses on elderly and vulnerable populations living in rural and mountainous regions where healthcare accessibility and continuity remain limited.

Within the proposed PHRESH workflow, wearable sensing technologies continuously acquire physiological parameters relevant for cardiovascular monitoring, including blood pressure, heart rate, oxygen saturation, physical activity levels, and optionally ECG-related information. Continuous physiological observation enables the collection of longitudinal health data outside conventional clinical environments and supports improved visibility into patient status evolution over time.

The collected physiological data are securely transmitted through IoMT communication infrastructures toward remote monitoring platforms and cloud-based services capable of supporting continuous telemetry and distributed healthcare supervision. Real-time access to physiological information may support healthcare professionals and caregivers in monitoring patient evolution remotely, especially for individuals requiring long-term cardiovascular supervision or living in isolated communities.

Artificial intelligence and machine learning mechanisms integrated within the PHRESH ecosystem may support anomaly detection, trend analysis, and intelligent alert prioritization. AI-assisted analytics may help identify abnormal physiological variations, sustained hypertension patterns, cardiovascular deterioration trends, or deviations from patient-specific baselines. Such approaches may facilitate earlier identification of potential risk situations and support prioritization of patients requiring clinical attention. Research on AI-assisted remote monitoring systems suggests that predictive analytics and continuous physiological monitoring may improve preventive healthcare strategies and support earlier intervention in chronic cardiovascular disease management (Khan et al, 2024).

The PHRESH platform may also provide remote monitoring dashboards capable of visualizing physiological trends, alert history, patient evolution, and anomaly notifications in real time. Such dashboards may support healthcare professionals in obtaining a more comprehensive overview of patient status and facilitate remote triage and follow-up activities. Intelligent alerting mechanisms may notify caregivers, healthcare professionals, or emergency response services when predefined thresholds or abnormal physiological patterns are detected.

Within the Romanian use case, the proposed clinical decision support approach is intended primarily as a conceptual and exploratory framework illustrating how connected healthcare technologies could support remote cardiovascular monitoring and continuity of care in underserved regions. As the Romanian consortium currently does not include an active clinical deployment partner, the proposed workflow is theoretical in nature and aims to demonstrate the potential integration of wearable monitoring, telemetry infrastructures, and AI-assisted analytics within future healthcare deployment scenarios.

Importantly, the PHRESH Romanian use case does not aim to replace physician expertise or autonomous medical diagnosis. Clinical decisions remain under the responsibility of qualified healthcare professionals, while AI-assisted analytics and telemetry systems are intended to support visibility, prioritization, and preventive intervention through continuous physiological observation and intelligent alerting mechanisms.

Within this framework, BEIA contributes by enabling the digital infrastructure supporting clinical decision-making processes rather than performing medical diagnosis itself. The company provides expertise in IoMT integration, secure telemetry systems, cloud-based communication infrastructures, wearable connectivity, remote sensing architectures, and distributed monitoring platforms capable of supporting continuous physiological data acquisition and secure transmission.

BEIA's expertise in telemonitoring systems, secure IoT communication infrastructures, cloud telemetry, emergency communication systems, and wearable integration supports the implementation of scalable remote healthcare architectures adapted to rural and geographically distributed environments. Through these contributions, BEIA supports the technological foundation necessary for enabling continuous monitoring, remote supervision, AI-assisted alerting, and connected healthcare communication within the PHRESH ecosystem.

3.4.4 Clinical Pathway model

The Romanian PHRESH use case proposes a conceptual clinical pathway model focused on improving access to primary healthcare services and supporting remote cardiovascular monitoring for elderly and vulnerable populations living in isolated rural and mountainous areas of the Apuseni region. The proposed pathway illustrates how wearable sensing technologies, IoMT communication infrastructures, secure telemetry systems, and AI-assisted analytics may support preventive healthcare and continuity of care in geographically underserved communities.

The envisioned pathway is theoretical in nature and intended to demonstrate the potential integration of connected healthcare technologies within rural healthcare ecosystems, particularly in regions affected by shortages of healthcare professionals, transportation difficulties, and limited access to specialized cardiovascular services. As the Romanian consortium currently does not include an active clinical deployment partner, the proposed workflow serves as an exploratory model for future pilot deployment and healthcare integration scenarios.

Step 1 – Patient Identification and Enrollment

The pathway begins with the identification of elderly or at-risk patients living in rural and mountainous communities within the Apuseni region. Potential beneficiaries may include patients diagnosed with hypertension, chronic cardiovascular diseases, diabetes, obesity, or other comorbidities associated with elevated cardiovascular and cerebrovascular risk.

Patient enrollment may be initiated through family doctors, local healthcare providers, community healthcare workers, or regional healthcare initiatives aiming to improve continuity of care for underserved populations. Due to the limited availability of healthcare personnel in isolated areas, the pathway emphasizes remote supervision and home-based monitoring approaches capable of reducing dependence on frequent in-person consultations.

Step 2 – Continuous Physiological Monitoring

Following enrollment, patients are equipped with wearable and non-invasive monitoring devices capable of continuously acquiring physiological parameters relevant for cardiovascular monitoring. Depending on the monitoring scenario and patient profile, the monitoring ecosystem may include:

- wearable blood pressure monitoring devices;
- heart rate sensors;
- pulse oximeters (SpO_2);
- activity monitoring devices;
- optional ECG-enabled wearable systems.

The monitoring process is designed to operate primarily in home-based and ambulatory environments, enabling continuous observation of physiological evolution outside traditional hospital settings. Continuous monitoring may facilitate earlier identification of abnormal physiological trends and support preventive healthcare strategies for elderly and vulnerable populations.

Wearable sensing technologies and remote patient monitoring systems have demonstrated potential for improving chronic cardiovascular disease management and continuity of care by enabling continuous physiological observation in non-clinical environments (Sultana et al., 2025).

Step 3 – Secure Data Transmission and Telemetry Integration

Physiological data collected by wearable devices are securely transmitted through IoMT communication infrastructures toward cloud-based monitoring platforms and remote supervision environments. Data transmission may rely on mobile connectivity, smartphones, IoT gateways, or distributed telemetry infrastructures adapted to rural deployment scenarios.

Within the PHRESH ecosystem, BEIA contributes expertise in IoMT telemetry, cloud communication systems, wearable integration, secure data transmission, and remote sensing infrastructures supporting continuous physiological monitoring and distributed healthcare communication. The communication architecture supports secure acquisition and transfer of physiological information while enabling remote access for authorized healthcare professionals and caregivers.

Given the geographical characteristics of the Apuseni region, the pathway also considers the challenges associated with rural connectivity and distributed healthcare infrastructures. Consequently, scalable telemetry and interoperable communication mechanisms are essential components of the envisioned monitoring ecosystem.

Step 4 – AI-Assisted Analysis and Risk Assessment

After acquisition and transmission, physiological data are processed through intelligent monitoring platforms capable of performing longitudinal analysis, anomaly detection, and cardiovascular risk assessment. Artificial intelligence and machine learning mechanisms may support:

- detection of abnormal blood pressure evolution;
- cardiovascular deterioration trend analysis;
- identification of irregular physiological patterns;
- intelligent prioritization of patient alerts;
- estimation of potential cardiovascular risk situations.

The purpose of AI-assisted analytics within the Romanian PHRESH use case is to support preventive healthcare and improve visibility into patient physiological evolution rather than replace physician expertise or autonomous diagnosis. AI-generated outputs are intended to assist healthcare professionals through intelligent monitoring, prioritization, and early warning functionalities.

Studies investigating AI-assisted cardiovascular monitoring suggest that predictive analytics combined with continuous physiological observation may contribute to earlier identification of deterioration indicators and support preventive intervention strategies (Khan et al., 2024).

Step 5 – Intelligent Alerting and Notification

When abnormal physiological values or predefined risk thresholds are identified, the PHRESH platform may generate intelligent alerts directed toward relevant stakeholders. Depending on the severity and context of the detected anomaly, notifications may be transmitted to:

- the patient;
- caregivers or family members;
- healthcare professionals;
- monitoring personnel;
- emergency response services in critical situations.

Alerting mechanisms may include mobile notifications, dashboard alerts, cloud-based messaging systems, or integrated communication channels. Continuous remote monitoring combined with intelligent alert prioritization may support earlier intervention and improve continuity of care for patients requiring long-term cardiovascular supervision.

Step 6 – Emergency Coordination and Remote Triage

In scenarios involving severe physiological deterioration or suspected cardiovascular emergencies, the PHRESH platform may support communication between patients, caregivers, healthcare providers, and emergency response teams. Remote access to patient physiological information may facilitate earlier triage decisions and improve continuity between home monitoring and emergency healthcare workflows.

The proposed pathway also considers the potential use of telemetry-supported communication between ambulance teams and healthcare facilities, enabling transmission of preliminary physiological information prior to hospital admission. Such capabilities may contribute to improved coordination and preparedness during emergency intervention scenarios, particularly in geographically isolated areas where transportation delays may significantly impact patient outcomes.

Step 7 – Longitudinal Monitoring and Preventive Care

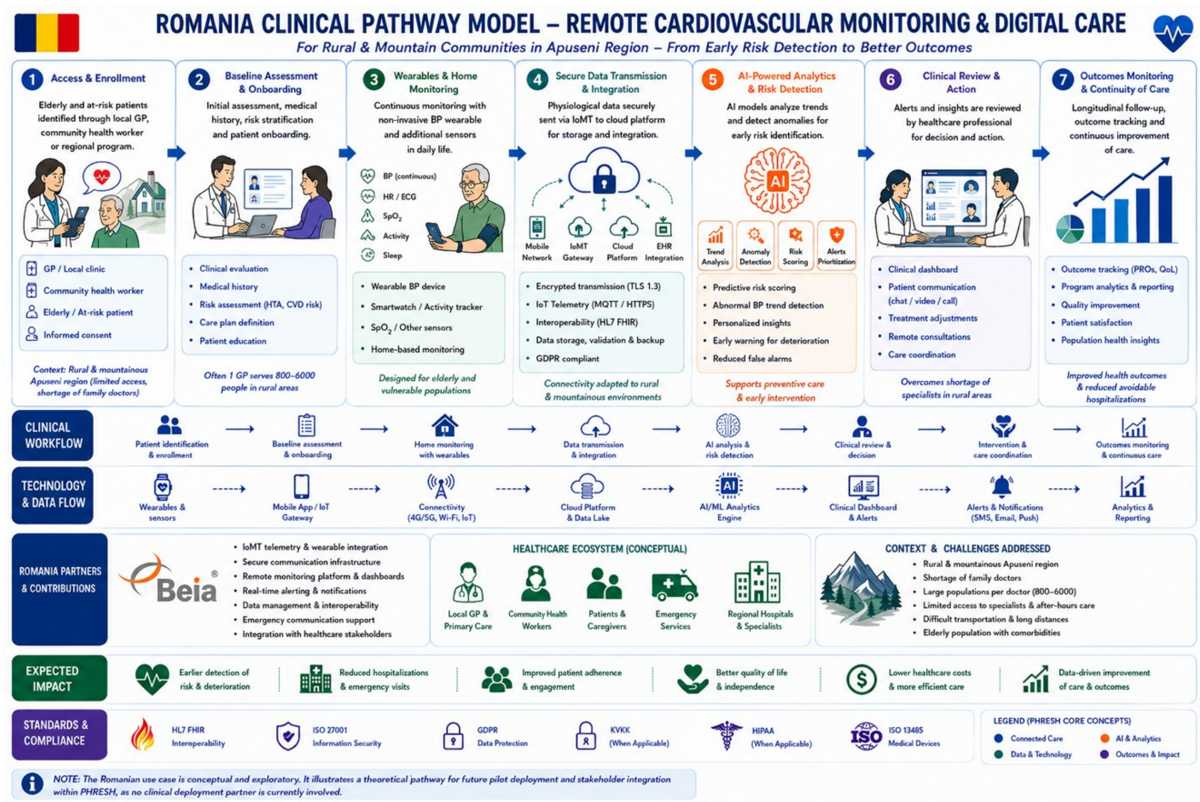
Following intervention or stabilization, physiological data remain securely stored within the monitoring infrastructure to support long-term supervision, chronic disease management, and preventive healthcare activities. Longitudinal physiological analysis may assist healthcare professionals in evaluating patient evolution, treatment adherence, and cardiovascular risk trends over time.

Continuous monitoring and remote follow-up may support:

- preventive healthcare strategies;
- chronic disease supervision;
- home-based monitoring;
- rehabilitation support;
- reduction of avoidable hospital visits;
- improved healthcare accessibility for isolated populations.

The Romanian PHRESH use case therefore illustrates a conceptual connected healthcare pathway capable of supporting healthcare accessibility, continuity of care, and preventive cardiovascular monitoring in rural mountainous environments through the integration of wearable technologies, secure telemetry systems, and AI-assisted digital health infrastructures.

Within this framework, BEIA acts as a technological enabler supporting the IoMT communication infrastructure, wearable integration, telemetry systems, cloud communication services, and secure monitoring architectures necessary for implementing distributed remote healthcare scenarios adapted to underserved rural environments.


ROMANIA CLINICAL PATHWAY MODEL – REMOTE CARDIOVASCULAR MONITORING & DIGITAL CARE
For Rural & Mountain Communities in Apuseni Region – From Early Risk Detection to Better Outcomes
1 Access & Enrollment
Elderly and at-risk patients identified through local GP, community health worker or regional program.
GP / Local clinic
Community health worker
Elderly / At-risk patient
Informed consent
Context: Rural & mountainous Apuseni region (limited access, shortage of family doctors)
2 Baseline Assessment & Onboarding
Initial assessment, medical history, risk stratification and patient onboarding.
Clinical evaluation
Medical history
Risk assessment (HTA, CVD risk)
Care plan definition
Patient education
Often 1 GP serves 800–6000 people in rural areas
3 Wearables & Home Monitoring
Continuous monitoring with non-invasive BP wearable and additional sensors in daily life.
BP (continuous)
HR / ECG
SpO2
Activity
Sleep
Wearable BP device
Smartwatch / Activity tracker
SpO2 / Other sensors
Home-based monitoring
Designed for elderly and vulnerable populations
4 Secure Data Transmission & Integration
Physiological data securely sent via IoMT to cloud platform for storage and integration.
Mobile Network
IoMT Gateway
Cloud Platform
EHR Integration
Encrypted transmission (TLS 1.3)
IoT Telemetry (MQTT / HTTPS)
Interoperability (HL7 FHIR)
Data storage, validation & backup
GDPR compliant
Connectivity adapted to rural & mountainous environments
5 AI-Powered Analytics & Risk Detection
AI models analyze trends and detect anomalies for early risk identification.
AI
Trend Analysis
Anomaly Detection
Risk Scoring
Alerts Prioritization
Predictive risk scoring
Abnormal BP trend detection
Personalized insights
Early warning for deterioration
Reduced false alarms
Supports preventive care & early intervention
6 Clinical Review & Action
Alerts and insights are reviewed by healthcare professional for decision and action.
Clinical dashboard
Patient communication (chat / video / call)
Treatment adjustments
Remote consultations
Care coordination
Overcomes shortage of specialists in rural areas
7 Outcomes Monitoring & Continuity of Care
Longitudinal follow-up, outcome tracking and continuous improvement of care.
Outcome tracking (PROs, QoL)
Program analytics & reporting
Quality improvement
Patient satisfaction
Population health insights
Improved health outcomes & reduced avoidable hospitalizations
CLINICAL WORKFLOW
Patient identification & enrollment
Baseline assessment & onboarding
Home monitoring with wearables
Data transmission & integration
AI analysis & risk detection
Clinical review & decision
Intervention & care coordination
Outcomes monitoring & continuous care
TECHNOLOGY & DATA FLOW
Wearables & sensors
Mobile App / IoT Gateway
Connectivity (4G/5G, Wi-Fi, IoT)
Cloud Platform & Data Lake
AI/ML Analytics Engine
Clinical Dashboard & Alerts
Alerts & Notifications (SMS, Email, Push)
Analytics & Reporting
ROMANIA PARTNERS & CONTRIBUTIONS
Beia
IoMT telemetry & wearable integration
Secure communication infrastructure
Remote monitoring platform & dashboards
Real-time alerting & notifications
Data management & interoperability
Emergency communication support
Integration with healthcare stakeholders
HEALTHCARE ECOSYSTEM (CONCEPTUAL)
Local GP & Primary Care
Community Health Workers
Patients & Caregivers
Emergency Services
Regional Hospitals & Specialists
CONTEXT & CHALLENGES ADDRESSED
Rural & mountainous Apuseni region
Shortage of family doctors
Large populations per doctor (800–6000)
Limited access to specialists & after-hours care
Difficult transportation & long distances
Elderly population with comorbidities
EXPECTED IMPACT
Earlier detection of risk & deterioration
Reduced hospitalizations & emergency visits
Improved patient adherence & engagement
Better quality of life & independence
Lower healthcare costs & more efficient care
Data-driven improvement of care & outcomes
STANDARDS & COMPLIANCE
HL7 FHIR Interoperability
ISO 27001 Information Security
GDPR Data Protection
KVKK (When Applicable)
HIPAA (When Applicable)
ISO 13485 Medical Devices
LEGEND (PHRESH CORE CONCEPTS)
Connected Care
AI & Analytics
Data & Technology
Outcomes & Impact
NOTE: The Romanian use case is conceptual and exploratory. It illustrates a theoretical pathway for future pilot deployment and stakeholder integration within PHRESH, as no clinical deployment partner is currently involved.

3.4.5 Challenges and novel solutions specification

The Romanian PHRESH use case addresses several interconnected technical, clinical, security, and operational challenges affecting healthcare accessibility and continuity of care in rural and mountainous regions such as the Apuseni area. Elderly populations living in geographically isolated communities frequently experience delayed access to diagnostics, shortage of healthcare professionals, transportation difficulties, and limited continuity of cardiovascular monitoring. The proposed conceptual PHRESH framework aims to explore how wearable sensing technologies, IoMT communication infrastructures, secure telemetry systems, and AI-assisted analytics may contribute to improving remote healthcare support and preventive cardiovascular monitoring in underserved environments.

Technical Challenges

One of the primary technical challenges associated with remote cardiovascular monitoring in rural and mountainous regions is ensuring reliable and continuous connectivity across geographically dispersed communities. The Apuseni region includes isolated villages and difficult terrain where communication infrastructures and internet availability may vary significantly. Continuous physiological monitoring requires stable and scalable telemetry systems capable of supporting secure real-time data transmission despite heterogeneous connectivity conditions.

Another major technical challenge concerns interoperability between heterogeneous wearable devices, IoMT platforms, cloud infrastructures, and healthcare information systems. Wearable sensors may use different communication protocols, sampling frequencies, and proprietary interfaces, increasing the complexity of data integration and synchronization. Additionally, large volumes of continuously generated physiological data require scalable cloud-based architectures capable of supporting real-time acquisition, validation, storage, and processing of distributed sensor streams.

Healthcare IoT ecosystems also require mechanisms for secure synchronization and reliable transmission of physiological data while minimizing latency and ensuring continuity of monitoring. Studies investigating IoMT-enabled healthcare infrastructures identify interoperability, scalability, real-time communication, and heterogeneous sensor integration among the most significant technical barriers affecting large-scale deployment of remote healthcare systems (Li et al., 2023).

Within the PHRESH Romanian use case, these challenges are addressed through the proposed use of secure IoMT telemetry architectures, interoperable communication infrastructures, wearable integration mechanisms, and cloud-based monitoring platforms capable of supporting distributed healthcare monitoring scenarios. BEIA contributes expertise in telemetry systems, IoT communication infrastructures, wearable integration, cloud-based communication, and secure remote sensing architectures supporting continuous physiological data acquisition and interoperability between connected healthcare components.

Clinical Challenges

Cardiovascular and cerebrovascular diseases often evolve progressively, while conventional healthcare workflows in rural regions remain primarily based on episodic consultations and intermittent physiological measurements. Consequently, physiological deterioration may remain undetected until symptoms become severe enough to require emergency intervention or hospitalization. Elderly patients and individuals with chronic cardiovascular conditions are particularly vulnerable to delayed diagnosis due to insufficient continuity of monitoring and reduced access to specialist healthcare services.

Another important clinical challenge concerns the management of large volumes of physiological data generated through continuous monitoring systems. Excessive alert generation and false-positive notifications may increase clinician workload and contribute to alert fatigue, particularly in resource-constrained healthcare environments. Effective remote monitoring therefore requires intelligent prioritization mechanisms capable of distinguishing clinically relevant deterioration from non-critical physiological variability.

The Romanian PHRESH use case addresses these challenges through the conceptual integration of AI-assisted monitoring and intelligent alerting mechanisms capable of supporting anomaly detection, trend analysis, and early identification of cardiovascular risk situations. Machine learning models may assist in detecting abnormal blood pressure evolution, sustained physiological deviations, and potential deterioration patterns while supporting more efficient prioritization of alerts and interventions. Continuous physiological observation combined with AI-assisted analytics may facilitate earlier identification of at-risk patients and support preventive healthcare strategies for vulnerable populations living in isolated areas.

Importantly, the proposed PHRESH framework does not aim to replace physician expertise or autonomous clinical decision-making. AI-assisted analytics are intended to support healthcare professionals through improved visibility, remote supervision, and prioritization of patient monitoring activities.

Security and Privacy Challenges

Healthcare monitoring systems involve the continuous acquisition, transmission, processing, and storage of highly sensitive physiological and personal data. Consequently, secure communication and data protection represent critical requirements for the PHRESH ecosystem. Challenges include ensuring GDPR compliance, preventing unauthorized access to medical data, maintaining secure authentication mechanisms, protecting cloud infrastructures, and preserving patient privacy during distributed monitoring activities.

The integration of wearable technologies and cloud-based telemetry systems introduces additional cybersecurity concerns related to remote connectivity, distributed IoMT infrastructures, and interoperability between heterogeneous healthcare systems. Secure transmission of physiological data and controlled access management are essential for maintaining trust and ensuring compliance with European healthcare data protection regulations.

The PHRESH Romanian use case proposes the use of encrypted communication channels, secure telemetry architectures, privacy-aware cloud services, and cybersecurity-oriented IoMT infrastructures to support secure physiological data transmission and remote monitoring activities. BEIA contributes expertise in secure IoT communication systems, telemetry infrastructures, cloud communication platforms, and secure remote sensing architectures capable of supporting resilient and privacy-aware healthcare communication environments. Relevant expertise includes previous developments related to secure IoT systems using dynamic isolation mechanisms and distributed telemetry infrastructures for remote monitoring scenarios.

Operational Challenges

The deployment of remote healthcare monitoring systems in rural mountainous regions also presents important operational challenges related to scalability, healthcare accessibility, patient engagement, and integration with existing healthcare workflows. The Apuseni region includes geographically dispersed communities where shortages of family doctors, transportation difficulties, and limited healthcare infrastructure significantly affect continuity of care and emergency response capabilities.

Patient adherence and acceptance of wearable monitoring technologies also represent important operational considerations. Elderly populations may require simplified interfaces, caregiver support, and user-friendly communication mechanisms in order to facilitate long-term participation in remote monitoring programs. Digital literacy limitations and reduced familiarity with connected healthcare technologies may also affect the adoption of wearable monitoring systems in certain communities.

Another challenge concerns the integration of remote monitoring solutions with heterogeneous healthcare infrastructures and fragmented healthcare workflows. Many healthcare providers operate isolated systems with limited interoperability capabilities, reducing continuity between home monitoring, primary healthcare, emergency services, and hospital-based care.

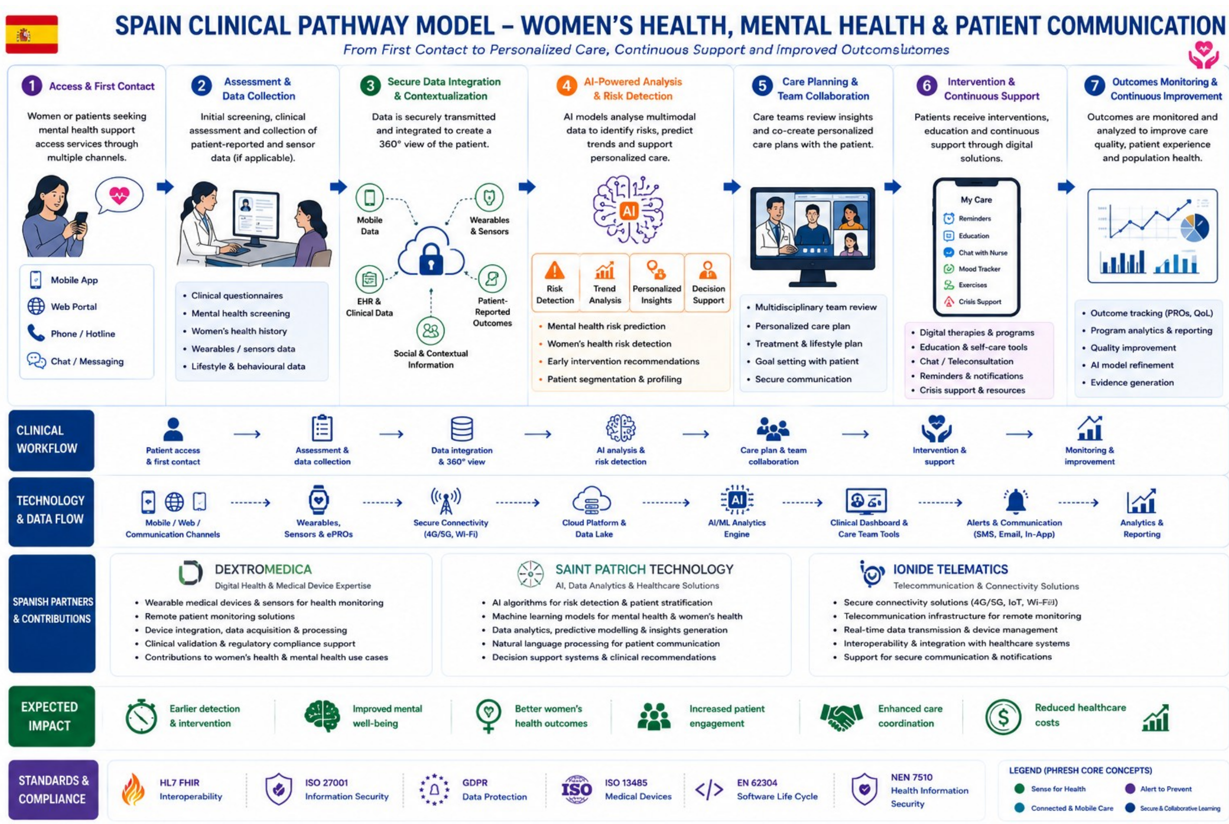
The Romanian PHRESH use case addresses these operational challenges through a conceptual and modular remote monitoring architecture capable of supporting scalable deployment, home-based monitoring, and gradual integration with healthcare stakeholders. The proposed approach emphasizes preventive healthcare, continuity of care, and accessibility for elderly and vulnerable populations living in geographically isolated environments.

As the Romanian use case currently represents a theoretical and exploratory framework without an active clinical deployment partner, the proposed solutions are intended primarily to illustrate how connected healthcare technologies and secure telemetry infrastructures could support future remote healthcare deployment scenarios in underserved rural regions.

Within this framework, BEIA acts as a technology enabler contributing expertise in IoMT telemetry, wearable integration, cloud communication systems, secure communication infrastructures, and remote monitoring architectures supporting distributed digital healthcare ecosystems adapted to rural and mountainous environments.

3.5 Spain - Women's Health, Mental Health, Patient Communication

The image presents a comprehensive clinical model for women's health, mental health and patient communication in Spain, developed in the context of the PHRESH project, showing how healthcare evolves from the first contact with the patient to the continuous monitoring of results through digital technologies, artificial intelligence and connected systems.



The following describes in detail each of the processes for each of the partners of the Spanish consortium:

3.5.1 Women's Health - DEXTROMEDICA

The **PHRESH** project, led by DEXTROMEDICA, addresses the optimization of healthcare in the Femtech field through standardization, decision support and process modeling.

1.7.1.1 Standardized *practices and variation in interventions*

The project uses **process mining** as an essential tool for decoding complex workflows. This technology makes it possible to visualize actual workflows, compare them with ideal processes, and identify **deviations and inefficiencies**. Standardization is achieved by:

- **Standardized protocols:** Compliance with regulations such as EN ISO 13485 and the establishment of operating procedures that ensure quality and safety.
- **Reduced variability:** By analyzing event logs, bottlenecks and unwanted variations in interventions are identified, allowing operations to be optimized and the quality of care to be raised.

1.7.1.2 *Clinical decision making*

DEXTROMEDICA seeks to empower data-driven decision-making through intelligent systems:

- **Peers-In-The-Loop (PITL):** A joint validation mechanism where AI-generated insights must be consciously reviewed by healthcare professionals, preventing it from being excessively delegated to the machine.
- **Customized Alert Systems:** Systems are designed that leverage integration with sensors and real-time data analytics to facilitate immediate and accurate interventions.
- **Conscious interaction:** Mechanisms such as quick check questionnaires or alerts are implemented that require deliberate responses before critical decisions are made.

1.7.1.3 *Clinical Pathway model*

Modelling clinical pathways is a fundamental task (Task 2.2) to standardise treatment and decision-making:

- **Identification of gaps:** These models are used to detect challenges that technological solutions must solve.
- **Personalization:** Despite standardization, the goal is for care routes to be dynamic and adapt to the specific needs of each patient, especially in the Femtech context (precision health).
- **Participation of experts:** Key Opinion Leaders (KOLs) and specialized services, such as Obstetrics and Gynecology, are involved in establishing the models in the hospital reality.

1.7.1.4 *Challenges and novel solutions specification*

The project identifies critical challenges and proposes cutting-edge solutions:

Challenges:

- **Historical biases:** The exclusion of women in medical research has created a data gap that affects the accuracy of treatments.
- **Fragmentation and privacy:** The difficulty in securely exchanging data between healthcare systems.
- **Integration complexity:** The challenge of connecting new automation tools with pre-existing infrastructures.

Innovative Solutions:

- **Agentic AI:** AI systems with greater autonomy capable of analysing, planning and collaborating as if they were a member of the clinical team.
- **Synthetic Data Generation:** Creation of realistic but anonymous data to train AI models without bias and without compromising patient privacy.
- **Hyperautomation:** Combining RPA and AI to automate routine tasks and optimize workflows in real-time.

Secure Integration Platform: A framework that ensures interoperability and GDPR compliance using advanced cryptographic techniques.

3.5.2 Mental Health - Saint Patrick Technology

1.7.3.1 Context

The PHRESH project is developed in a context marked by the **ageing of the European population** and growing inequalities in access to health services, especially in **rural or emergency settings**. Current solutions are insufficient to ensure inclusive and evidence-based care. There is an urgent need to transform healthcare through a comprehensive framework that combines advanced technologies, data security and accessibility, specifically addressing gaps in the "emptied Spain", where the population is often older and lives alone.

1.7.3.2 Standardized practices and variation in interventions

One of the pillars of the project is to overcome the lack of comprehensive and adaptive systems that today present a high variability in their application. PHRESH seeks **to efficiently standardize treatment** and patient care. The project identifies that current interventions often do not reflect the diversity of populations (data biases) and lack a framework that articulates all technological capacities in a coherent way. To mitigate this, the definition and standardization of procedures that guarantee more coherent and evidence-based interventions is proposed

1.7.3.3 Clinical decision making

The system is designed to act as critical **support in the decision-making of** mental health professionals. Through the "smart health co-pilots", the aim is to:

- **Optimize workload:** By automating routine tasks (reporting, data collection), the professional can focus on higher-value tasks, such as making accurate diagnoses and establishing personalized health criteria.
- **Provide contextualized information:** Language models (LLMs) process large volumes of data to generate clear summaries that help clinicians make informed, evidence-based decisions.

1.7.3.4 Clinical Pathway model

Within the work plan (Task 2.2), the project focuses on **the modelling of the clinical pathway** for each use case. This model has the following functions:

- **Standardization:** To serve as a basis for unifying care and clinical decision-making.
- **Identifying gaps:** Detecting challenges to propose novel solutions.
- **Expert collaboration:** Engage key opinion leaders (KOLs) and internal experts to translate research concepts into actual practice in hospital settings, initially focusing on anxiety **and depression**.

1.7.3.5 Challenges and novel solutions specification

PHRESH identifies complex challenges and proposes differential solutions:

Challenges:

- **Security and Privacy:** Comply with the GDPR and the EU AI Act without compromising interoperability between systems.
- **Data Quality:** Overcoming biases in AI models and the difficulty of capturing emotional subtleties in mental health.
- **Accessibility:** Adapting technology to older people with low digital literacy.

Innovative Solutions:

- **Healthcare Co-pilots:** AI-based support tools to assist in critical decisions.
- **Continuous Assessment:** A framework that combines collaborative learning and advanced validation to ensure system reliability.
- **Proactive Early Detection:** Systems integrated into mobile devices and home assistants that identify critical changes in a non-intrusive way.

3.5.3 Patient Communication – IONIDE Telematics

1.7.3.6 Context

The **PHRESH** (Patient Health Response in Emergent and Secure Habitats for Connected Healthcare) project, led by IONIDE, addresses the modernization of hospital environments through solutions based on artificial intelligence, emotional analytics and data security. The following is the response to the key points discussed:

1.7.3.7 Standardized practices and variation in interventions

The project recognizes that the workload and hospital stress make timely care difficult. In contrast to the current "one size fits all" proposals, PHRESH seeks to introduce **personalized and adaptive interfaces**.

- **Adaptation to diversity:** The system is designed to accommodate individual variations such as **patients' language, age, education level, and potential disabilities**.
- **Dynamic interventions:** The virtual assistant does not offer static responses; on the contrary, it proposes specific interventions according to the patient's condition, such as **guided relaxation exercises, mindfulness or recommendations for well-being content** (music or audiobooks) adapted to whether stress or sadness is detected.

1.7.3.8 Clinical decision making

PHRESH acts as a support tool for healthcare workers to make more accurate and humane decisions:

- **Emotional History:** The system generates a detailed record of the patient's emotions, allowing clinicians to observe trends and patterns to make **informed clinical decisions**.
- **Automatic reporting:** The assistant generates reports on patient progress, helping staff identify critical changes without increasing their administrative burden.
- **Smart alerts:** In critical situations (high levels of anxiety or pain detected by voice and language), the system activates **alert protocols** for healthcare personnel to intervene immediately and specifically.
- **Explainability:** To strengthen clinical confidence, **Chain of Thought techniques are used**, which offer clear explanations as to why the AI has generated a given decision or suggestion.

1.7.3.9 Clinical Pathway model

Within the work plan (Task 2.2), the project specifically contemplates the **Analysis of clinical pathways**.

- **Flow Adaptation:** Hospital workflows are adapted to improve operational efficiency and user experience.
- **Simulation and validation:** Simulations of clinical processes are carried out to validate improvements in staff coordination.
- **Automatic prioritization:** The model seeks to optimize alert management through the **automatic prioritization of actions**, based on improved monitoring of the patient's physical and emotional state.

1.7.3.10 Challenges and novel solutions specification

The project identifies current technological gaps and proposes disruptive solutions divided into three main modules:

Patient-Assistant Interaction:

- Challenge: The lack of transparency of AI and the difficulty of integration with electronic medical records (EHRs).
- Solution: A **Dynamic UI/UX System based on AI** that generates interfaces that evolve according to actual usage and patient feedback.

Emotional Analysis and Prioritization:

- Challenge: Emotion detection models are often designed for call centers and fail in hospitals due to voice patterns altered by **pain or anxiety**.
- Solution: Language models (LLMs) **specifically trained with real hospital data** and capable of running in a hybrid way (on-premises/cloud) to ensure speed and privacy.

PET, Monitoring and Reliability (AI Act):

- Challenge: Traditional anonymization methods are vulnerable to inference attacks on AI models.
- Solution: Implementation of **Privacy Enhanced Technologies (PETs)**, such as differential privacy and homomorphic encryption, along with an **LLMOps** governance framework to ensure compliance with the EU AI Regulation.

3.6 Türkiye – AI-driven Decision Support for Lung Diseases

3.6.1 Context

Acute exacerbation of chronic obstructive pulmonary disease (AECOPD) often leads to hospitalization, prolonged stay, and high readmission, with large costs and resource use. Recovery after discharge is a vulnerable period with variable trajectories and frequent complications. Continuous or frequent monitoring of vital signs [heart rate (HR), respiratory rate (RR), oxygen saturation (SpO_2), activity] and integration into remote care models is feasible and acceptable in other conditions and increasingly in COPD. Digital and wearable stethoscopes enable objective, shareable lung sounds and open the door to AI-based auscultation and long-term ambulatory monitoring.

3.6.2 Standardized practices and variation in interventions

Standard AECOPD care focuses on symptom relief, gas exchange, comorbidity management, and safe discharge, but there is marked variation in length of stay and readmission risk. Current prediction models mainly target prolonged stay or readmission, using labs, vital signs and prior utilization, not detailed recovery physiology. Remote monitoring trials in COPD have largely aimed at exacerbation detection, with mixed impact on outcomes and adherence challenges after discharge. There is no established standard for using serial lung sounds plus continuous vitals specifically to quantify healing and anticipate discharge readiness.

3.6.3 Clinical decision making

Machine-learning models already support decisions about length of stay and readmission risk in AECOPD using interpretable approaches such as random forests and SHAP. Continuous RR and HR in the weeks after discharge show measurable changes prior to clinical events, supporting dynamic, time-series–based decision support. AI-based lung sound analysis (spectrogram + deep learning) can distinguish normal from abnormal patterns (e.g., wheeze, crackles) and is seen as a key component of intelligent/digital stethoscopes. Together, these approaches justify an AI system that tracks individual recovery curves of lung sounds + vitals to inform discharge timing and identify delayed healing rather than focusing on new exacerbations.

Core Elements of a Recovery-Focused Pathway

Element	Recovery Oriented Role
In-hospital phase	Daily manual + digital auscultation; continuous RR/HR/SpO_2 to characterize "healing" trajectory and risk of prolonged stay
Post-discharge week	Home recordings with digital stethoscope + wearable band to confirm continued improvement and detect stalled recovery

AI analytics	Time-series models mapping from sound/vitals trends to outcomes such as length of stay and recovery class

3.6.4 Clinical Pathway model

Target group: Patients hospitalized with AECOPD, from admission to 7 days post-discharge.

In-hospital steps:

Baseline: Manual + digital auscultation at standard chest sites; initiate continuous or high-frequency HR, RR, SpO_2 monitoring when feasible.

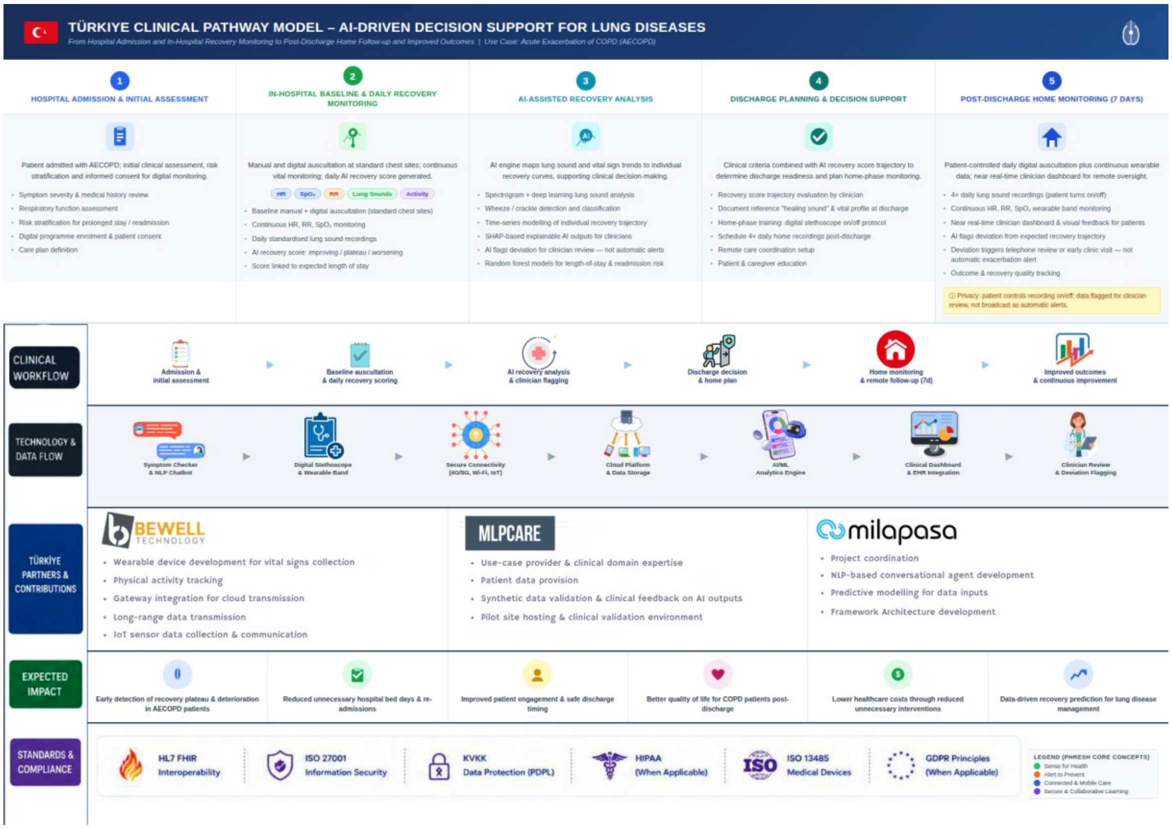
Daily follow-up: Repeat standardized lung sound recordings and summarize vital-sign trends; AI module outputs a recovery score (e.g., improving vs. plateau vs. worsening) linked to expected length of stay.

Discharge planning: Combine clinical criteria with recovery score trajectory; document "healing sound" and vitals pattern at discharge as reference for home phase.

Home (first 7 days): Scheduled daily digital auscultation plus continuous band data; near real-time dashboards for clinicians and simple visual feedback for patients.

To ensure patient privacy, lung sounds will be recorded four times a day at home, and the patient will be taught how to turn the recording on and off.

AI flags deviation from expected recovery (e.g., persistent abnormal sounds or non-improving RR/HR/SpO_2) for telephone review or early clinic assessment rather than automatic exacerbation alerts.



3.6.5 Challenges and novel solutions specification

Challenges

- High burden and attrition when enrolling patients in digital monitoring directly from AECOPD admissions.
- Noise, device variability, and mixed respiratory sounds complicate AI auscultation, requiring large, well-labeled datasets and robust denoising.
- Remote monitoring evidence in COPD is heterogeneous, and many RPM trials have not clearly improved outcomes.

Novel solutions for the project

- Focus explicitly on recovery prediction and safe discharge, a less explored but clinically relevant outcome distinct from exacerbation prediction, leveraging existing LOS/readmission ML frameworks.
- Use a paired manual + digital stethoscope protocol in hospital to label sound changes as "healing" vs. "non-healing," grounding AI models in clinician-validated trajectories.

- Combine lung sounds with continuous vitals in a personalized, time-series model of each patient's recovery, similar to dynamic RPM approaches but with recovery, not relapse, as the target.

Summary

Evidence supports digital stethoscopes, AI lung-sound analysis, and wearable vital-sign monitoring in COPD, but prior work has mainly targeted exacerbation prediction and readmission risk. Our PHRESH pathway can fill a gap by using in-hospital and early post-discharge sound + vital data to characterize and predict recovery, guide discharge timing, and potentially reduce unnecessary bed days and interventions.

3.7 United Kingdom – Home based CVD monitoring, prevention and care

3.7.1 Context

The UK health system faces intense pressure from an ageing population with growing numbers of long-term conditions. There are also significant difficulties in recruiting and retaining staff, and service strain is evident across primary, secondary and emergency care. Accident and emergency waiting time standards have not been met for over a decade, and primary care access remains under pressure.

In response, the UK government has published its 10-year health plan for England, which is now being put into action. The plan is built on three major shifts: moving care from hospital to community, moving to digital services, and shifting from treating sickness to actively preventing it. As part of this, the NHS explicitly names CVD as a national priority. For cardiovascular disease, the target is a 25% reduction in premature deaths. NHS England has also identified that cardiovascular disease is the single biggest condition where lives can be saved over the next 10 years, with a goal to prevent over 150,000 heart attacks, strokes, and dementia cases by 2029. It currently affects around seven million people in the UK, causing one in four premature deaths, and a key target is to reduce premature deaths from heart disease and strokes by twenty five percent within the next decade. Currently the UK lacks an appropriate and effective solution to handle these types of patient's long term health needs from any part of the country. Therefore, HIGOE in the UK are developing an end-to-end platform incorporating remote monitoring and care of CVD patients at home, with improved care pathways which result in lower hospital admissions.

3.7.2 Standardized practices and variation in interventions

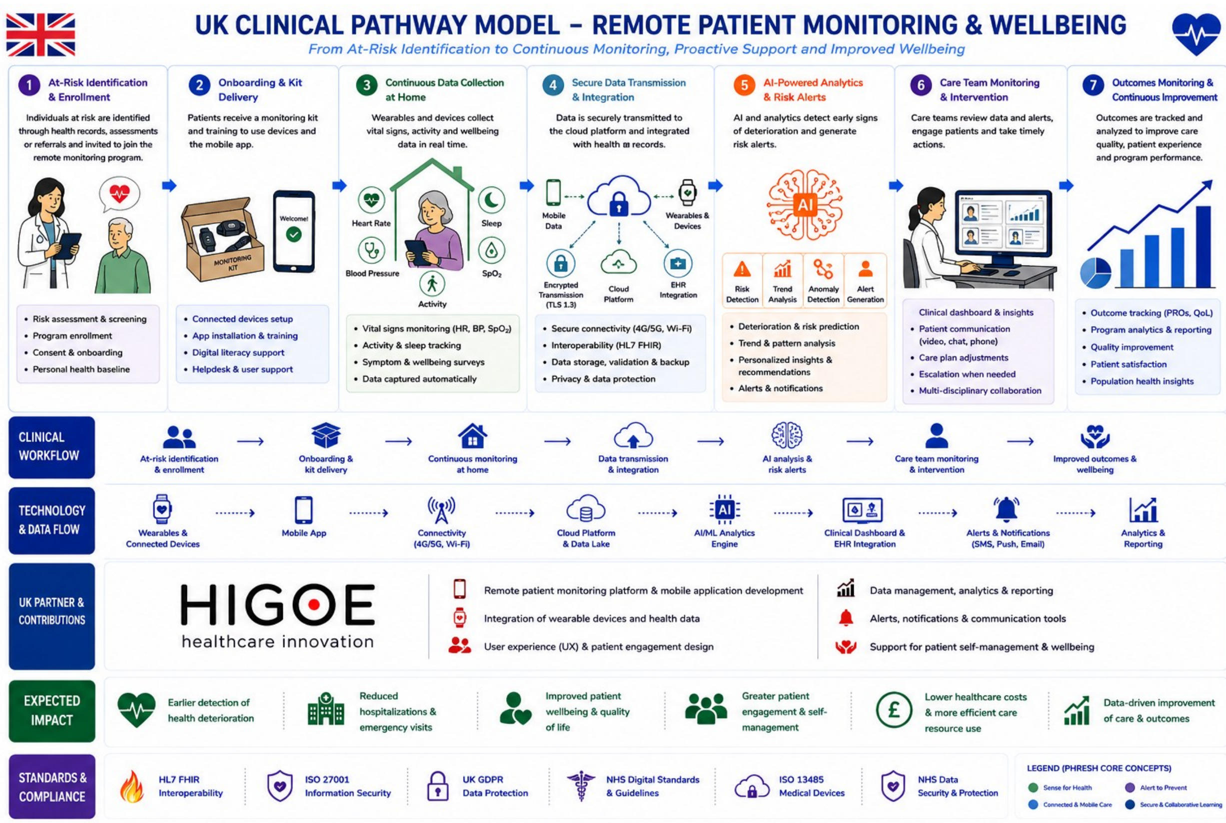
Currently the UK health system has some useful initiatives to tackle the issues around CVD but unfortunately there is a large variation on implementation, and they are not on a large enough scale for impacting CVD patient hospital admission or early death. These include looking at doing some ad hoc local health checks and investigating patients who are undiagnosed or undertreated. In addition, there is a home care model in the UK, called “virtual wards” or “hospital at home” but this is only targeted at individuals (including cardiac and cardiovascular) who visit a hospital for acute care and are given the option to receive very brief remote monitoring, and treatment in their own home, preventing unnecessary hospital admissions. Therefore, HIGOE within the UK plan a more holistic, joined up approach to deliver a reliable and innovative digital healthcare platform to manage CVD patients early with consistent and continuous support. This strategy will go towards reducing the considerable number of premature deaths in the UK.

3.7.3 Clinical decision making

Reliable and impactful decision making by clinicians for CVD patients at home is constrained by various factors, which include lack of appropriate care pathways, access to the right health data and technological infrastructure (that is also secure and privacy preserving) and use of ethical and responsible AI tools. In the UK, HIGOE are therefore taking an inclusive approach to supporting clinicians and patients which looks at new care pathways and ways of working, collection and analysis of the appropriate health data using AI, that shifts care to be more personalised and preventative at home. At the same time it allows for easy and seamless transfer of health data from home to ambulance and to health care setting in emergency or other health visits

3.7.4 Clinical Pathway model

The clinical pathway model is based on placing patient at the centre of care and at the same time giving all stakeholders tools to perform their role efficiently and effectively. The digital health platform by HIGOE is designed to support the clinical pathway by innovations across the 4 key themes of PHRESH, which include sense for health, alert to prevent, connected transport and secure and collaborative learning. The platform incorporates a new clinical pathway, which is depicted with the traditional model below.



3.7.5 Challenges and novel solutions specification

There are many challenges with developing a digital health platform for home care of CVD patients that encompasses a clinical workflow that has positive and viable outcomes for patients and at the same utilises latest innovations including AI. Some of the challenges relate to working with a fragmented healthcare system, obtaining the right health data, reliable monitoring devices, integration with external health systems, changing regulatory landscape, data privacy and data security measures that require continuous improvement to adapt to the evolving threat landscape.

The novel solutions considered for the UK platform encompass :

- Development and use of novel healthcare specific AI models to fuse locally carefully selected multi source health data (including wearables and sensors) for deep analysis, insights, support clinical decision making and to prepare personalised and preventative care plans and interventions.

- Use of ethical and responsible AI throughout the AI lifecycle to ensure reliable outputs and to reduce likelihood of mistakes that could affect patient care. Also continuous monitoring of AI tools to ensure any issues are flagged early and action taken such as AI drift, bias, efficiency, and hallucination as this will provide greater confidence to patients and clinicians.

- Seamless transfer of data throughout the whole patient journey allowing latest health status and health information being visible to connected healthcare providers and to emergency transport providers (Ambulance).

- Automated tools to reduce administrative tasks, such as referrals for specialist treatment.

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