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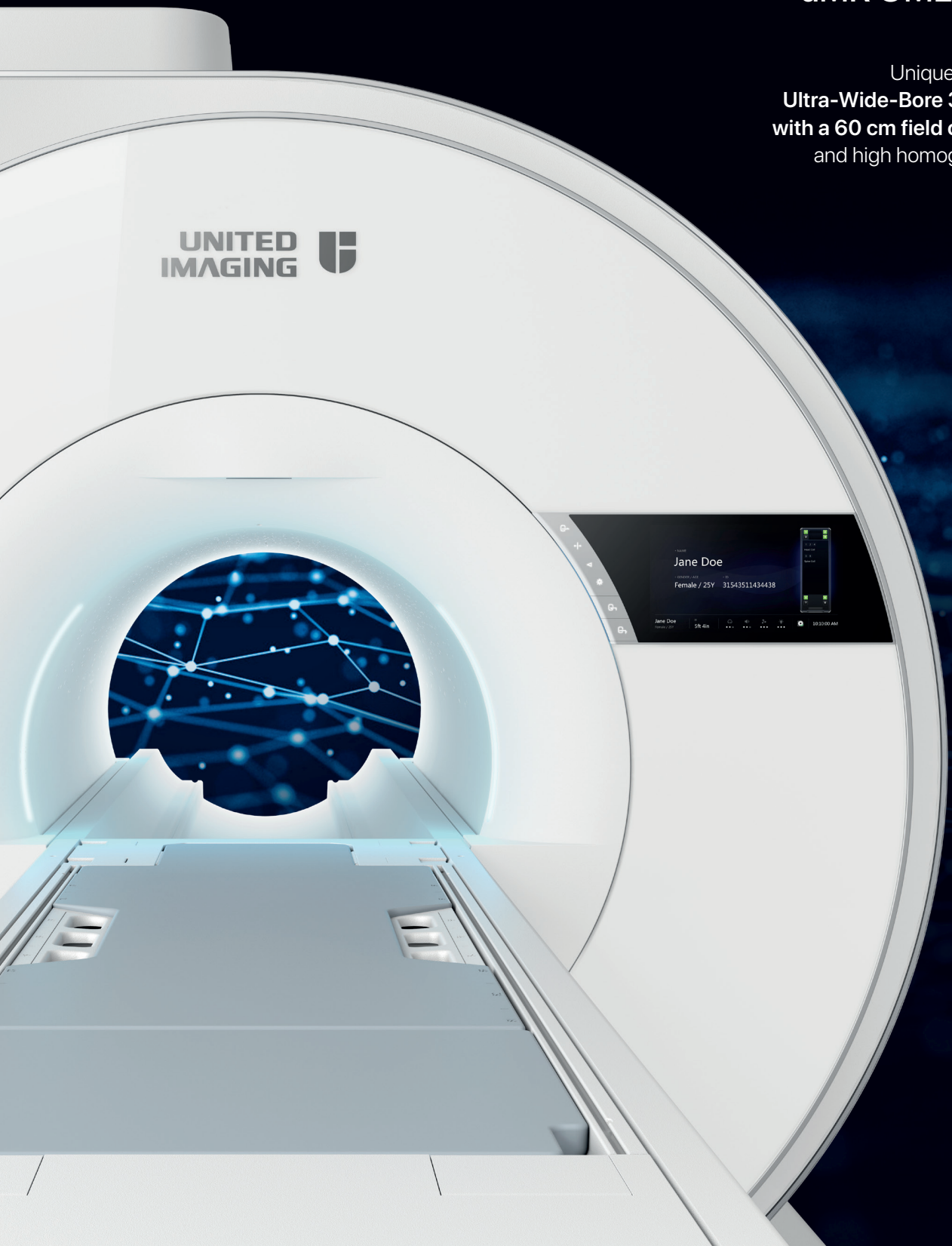

MORE INFO:

Editorial

STEPHEN LIEBER

Executive Chairman/Co-Founder | Alliance for Smart Healthcare Excellence | USA | Editor-in-Chief IT

Technological Integration & AI

Healthcare is moving from disconnected digitisation to purposeful integration where data, workflows and people align around patient value. The shift demands more than new tools: it requires upgraded infrastructure, clear governance, skilled teams and a culture that treats technology as an enabler of safer, faster, fairer care.

AI now sits at the centre of this transformation. Deployed well, it supports clinical decision-making, streamlines operations and extends scarce expertise. Deployed poorly, it adds noise, creates silos and erodes trust. The difference lies in design, evidence, accountability and the ability to embed systems into everyday practice.

This issue examines how organisations are integrating technology and AI to lift quality, efficiency and resilience. The contributions span EHR and data stewardship, trustworthy digital health, radiology learnings, smart hospital transformation, medication safety, 3D printing and automation as well as cybersecurity. Our authors chart pragmatic pathways to integrate systems, govern AI, operationalise data, scale proven innovations and protect patients while supporting the workforce.

Dr. Quoc Duy Vo considers how radiology can adapt AI innovations from automotive, finance and manufacturing to enhance workflows and strategic management.

Prof. Dr. Karl A. Stroetmann and Velimir Kanev outline how NeuroGenAI links leading EU centres to build GenAI for neurology, focusing on disease trajectories, synthetic data, digital twins and multimodal LLMs with ethics embedded.

Aarthi Janakiraman and Debarati Sengupta describe how AI, robotics and digital innovation are turning hospitals into predictive, patient-centred ecosystems.

Dr. Anna K. S. von Eiff and Prof. Wilfried von Eiff investigate how smart cabinets enhance medication safety and efficiency while noting barriers to adoption in German hospitals.

Stephen Lieber introduces the Smart Hospital Maturity Model as a framework to help hospitals adopt smart technologies, strengthen operations and achieve full digital integration.

Naomi L. Nathan et al. examine how 3D printing is transforming healthcare through innovation and sustainability.

Dr. Luis Concepción Aramendía et al. report how Valencia's AI orchestration system transformed emergency radiology across 29 hospitals.

Jenna Anderson et al. analyse global trends in EHR procurement and clinician satisfaction, showing how alignment of infrastructure, training, governance and personalisation drives better outcomes.

Felix Gille and Federica Zavattaro map a stepwise route to trustworthy digital health through context, levers, indicators and refinement.

Marita Huamán Peralta and Alan Zettelmann explain how the Own Your Data framework helps healthcare organisations turn fragmented data into a strategic driver of efficiency and innovation.

Armin Scheuer and Abdulaziz S. Alhomod trace how Saudi Arabia's Vision 2030 is reshaping healthcare through digital innovation, strategic reforms and global partnerships.

Arthur Ajwang demonstrates how individualised 3D-printed fetoscopes improved monitoring, reduced emergency caesarean sections, prevented deaths and lifted satisfaction in a Kenyan maternity ward.

Prof. Maddalena Illario highlights how cross-disciplinary training, data sharing and process-based teams can embed antimicrobial resistance management and support a 2030 EU data space vision.

Dr. Frederic Llordachs explores the NHS 2025 vision of hospitals as decentralised digital services, calling for strategic AI integration, virtual care and unified records.

Andrew Colbert assesses pressures on independent practices and positions private equity as one partnership option with trade-offs that require careful governance.

Dr. Ian Weissman and Maria Ortlieb set out the RETAIN initiative as a practical, evidence-based response to the radiology workforce shortage through leadership, education and peer support.

José A. Cano argues that robust cybersecurity is essential to protect patient data, preserve clinical accuracy and sustain trust in healthcare delivery.

I hope you will find this collection insightful, practical and actionable for the work ahead.

Happy reading!

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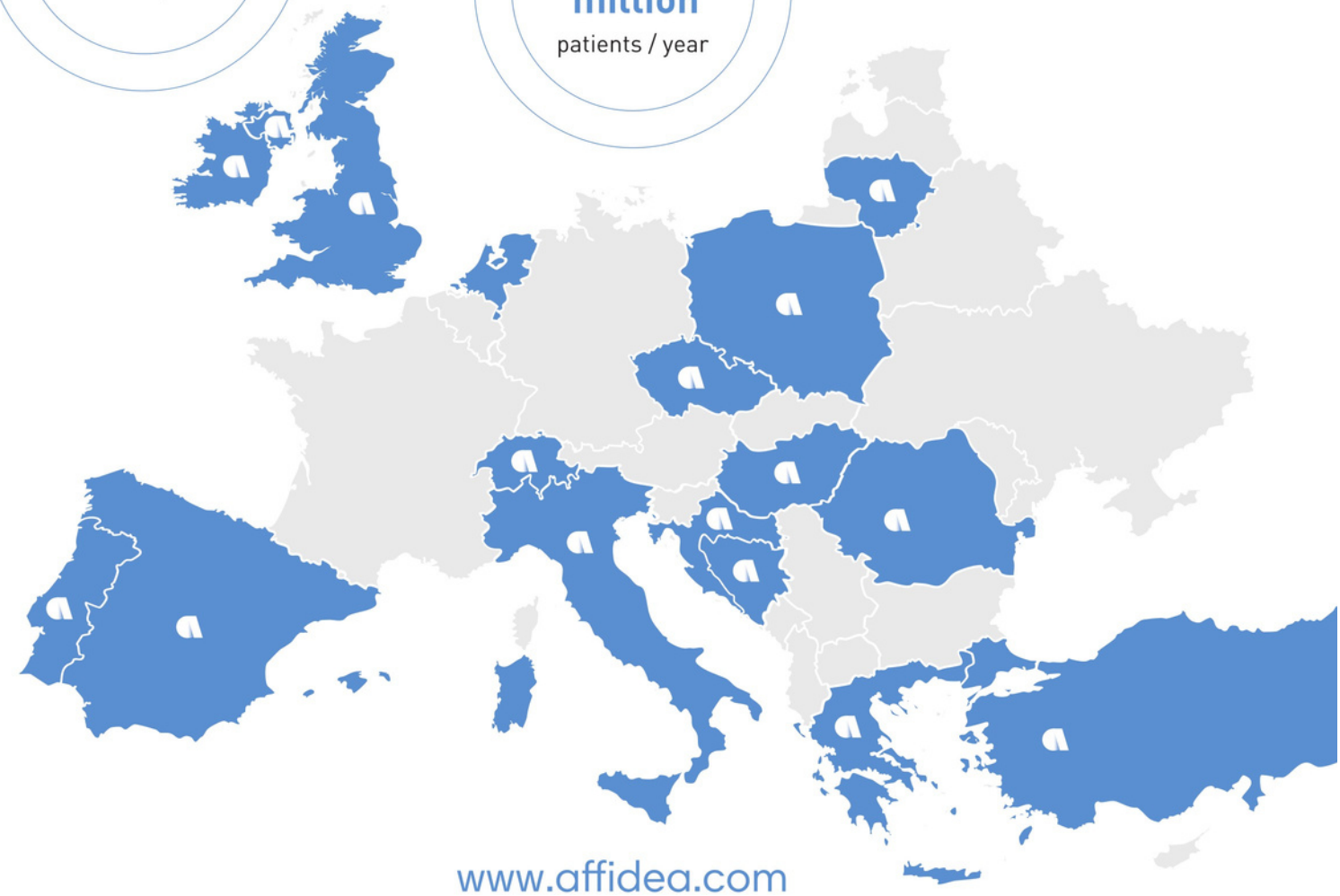

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Arthur Ajwang is a Kenyan medical doctor pursuing a master's in general surgery. Passionate about medical technology for prompt diagnosis and care, he is co-director of the Global Health Catalyst and Kenya country director, and a country board member of Inspire to Live – World Campus. Arthur is founder and CEO of Sun City Silicon Hub, heads research and innovation at Uzima University School of Medicine, and serves on Global Oncology University faculty (Phytomedicine).

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Dr. Abdulaziz Alhomod serves as Chief Innovation Officer at Seha Virtual Hospital, Consultant at King Fahad Medical City, and Assistant Professor at King Saud University. He is US board-certified in emergency medicine and clinical informatics, with a focus on digital health transformation and global health.

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Jenna Anderson, USA

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Dimitri Belov, Germany

Dimitri Belov, Head of Health Marketing at Düsseldorf Convention since 2022, leverages over a decade of experience in health tourism and strategic marketing. Previously with Visit Düsseldorf, he led efforts to position the city as a global healthcare destination. Dimitri specialises in acquiring medical congresses and attracting medical travellers, fostering partnerships with top medical facilities, and developing ambassador programmes to enhance Düsseldorf's profile in health tourism and congress hosting.

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Miguel Cabrer is Investor and Founder of Idonia, a medical imaging interoperability platform that empowers patients and doctors to access, share and visualise images, documents and AI. He has served as CIO of hospitals in Spain and the Balearic Health Region, and was on the HIMSS EMEA Governing Council (2006–2013). He founded MEDTING, acquired by BestDoctors in 2012. From 2012 to 2016, he led BestDoctors' digital transformation before its sale to Teladoc in 2017.

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Jonathan Christensen, USA

Jonathan Christensen, Senior Insights Director, is leading a team of KLAS analysts focused on imaging research, clinical software and medical research for international markets. His role led him to engage with executive leaders from around the world to identify research needs for the industry that will benefit vendors, providers and investors. His goal is to identify gaps in market understanding and then help close those gaps to spur the industry forward and ultimately deliver better healthcare for patients.

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Ciclus Group, Peru

Ciclus Group is a consulting firm based in Peru with over 19 years of experience in business transformation through data strategy and innovation. Its OYD Framework aligns data, technology and strategy to deliver measurable results with a guaranteed ROI. Its services include data-driven business models, data literacy programmes and commercial and operational optimisation. Ciclus supports organisations in using data to improve decision-making and drive sustainable growth.

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Andrew Colbert, USA

Andrew Colbert is a senior managing director and founding member of Ziegler's Healthcare Investment Banking practice. Andrew has represented over 60 physician groups on innovative transactions totaling over $6 billion (€5.1 billion) in value. He specialises in advising physician groups on strategic and financing alternatives including PSAs, mergers/acquisitions, health system partnerships, joint ventures, MSOs, strategic partnerships, private equity deals and capital investments.

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Dr. Luis Concepción Aramendía holds degrees in Medicine and Surgery, a Master's in Healthcare Services Management and a Doctorate in Medicine and Surgery. A certified specialist in Radiodiagnostics with European diplomas in Radiology and Neuroradiology, he has practised since 1998 and is Head of Radiodiagnostic Service at Hospital General Universitario Dr Balmis. He also teaches at the University of Alicante and serves on boards of Spanish radiological and medical associations.

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Everest Group is a leading global research firm helping business leaders make confident decisions. The firm provides actionable research into the world's cutting-edge Science & Technology innovations and delivers the tools to identify and understand upcoming innovations across R&D science and technology domains. Everest Group also investigates the enablers to effective innovation, including innovation processes and toolkits and critical mega forces for navigating a changing future.

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Felix Gille, PhD, is a researcher at the Digital Society Initiative, University of Zurich, focusing on public trust in health systems. He also serves as an Enterprise Architect at the Federal Chancellery of Switzerland, where he contributes to the development of a national trustworthy data ecosystem. A summary of his research is available open access in his book *What Is Public Trust in the Health System? Insights* into Health Data Use, published by Policy Press in 2023.

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Aarthi Janakiraman has more than 15 years of experience in technology research and strategic consulting. She has broad experience identifying and assessing the impact of emerging trends and technologies in the healthcare, F&B and CPG industries. Her expertise lies in opportunity assessment, IP management, R&D landscaping and technology road mapping and innovation ecosystem analysis.

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Stephen Lieber is the Chief Executive Officer of the Alliance for Smart Healthcare Excellence, a not-for-profit organisation which provides professional education and resources focused on smart care technologies and processes to health systems and companies. Previously, he also served as CEO of HIMSS and Chief Analytics Officer at CHIME. Known for his organisational growth skills, he has a strong executive network and international recognition. As a consultant, he provides guidance on governance, strategic analysis, international expansion and digital media, specialising on not-for-profit management, healthcare policy and health information technology. Additionally, he advises startups on technical and business matters.

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Dr. Frederic Llordachs graduated in Medicine and Surgery, with an MBA from ESADE Business School. He co-founded Doctoralia, now part of the Docplanner Group, the world's largest healthcare search platform and a leading European digital health unicorn. He has contributed to the growth of several digital health initiatives and now leads Llamalitica, a GenAI solution that enhances doctor–patient communication by eliminating non-clinical tasks for physicians.

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Anna K. S. von Eiff is a resident physician (internal medicine, emergency medicine, intensive and palliative care) with working experience in Switzerland and Germany. She is also an extra occupational study of Business Administration (MBA).

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Wilfried von Eiff is a professor in hospital management at the University of Münster and president of the German Hospital Procurement Management Congress. His research is focused on supply chain management, health technology assessment, circular economy, digitalisation and AI in health care and process reengineering. He co-operates with European Health Management Association and is also a member of the board of directors at Kerckhoff Clinic Heart and Lung Campus Bad Nauheim.

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Dr. Ian Weissman is a radiologist from Milwaukee and a speaker for the ACR's Radiology Leadership Institute. He serves on the RSNA's Government Relations Committee and has held national roles, including Chair of ACR's Veterans' Affairs and Patient and Family-Centred Care Outreach Committees. A past president of the Wisconsin Radiological Society, he received the 2023 RLI Impact Award and 2019 ACR Advocate of the Year. He champions innovation to improve care and address the workforce shortage.

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Federica Zavattaro, Switzerland

Federica Zavattaro is a PhD candidate in Digital and Mobile Health at the Digital Society Initiative, University of Zurich. Her research, featured in The Milbank Quarterly and Health Policy, explores how policymakers can foster public trust in health data sharing, including a collaboration with WHO's Data and Digital Health Unit to develop a tool supporting trust-building through policymaking.

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Alan Zettelmann, UAE

Alan Zettelmann, a partner at Innovation 360 Group AB in UAE, has over 17 years of experience in technology and entrepreneurship. Holding a Master's in Business Innovation and Administration from Deusto, he won Austria's 2017 Innovation Award. Based in Dubai, he's known for strategic innovation consulting and measuring organisations' 'Innovation IQ.' Founder of INNOCONSULT, he focuses on Space travel, Immortality and ESG projects, while teaching at CEU, Deusto Business School and EOI.

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— Nora Naisbitt, Founder

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MORE INFO:

Spotlight

Düsseldorf Welcomes ICCA Future of Healthcare Meetings

The Düsseldorf Convention hosted the ICCA Future of Healthcare Meetings on October 1–3, 2025, at the Congress Center Düsseldorf (CCD). Association leaders, healthcare professionals and meeting suppliers explored how medical meetings can adapt to changing regulations, digital transformation, patient involvement and sustainability objectives, while offering meaningful networking opportunities and highlighting Düsseldorf's strong infrastructure and vibrant culture.

DIMITRI BELOV

Head of Health Marketing I Düsseldorf Convention I Düsseldorf, Germany

key points

- Düsseldorf hosted ICCA Future of Healthcare Meetings on 1–3 October 2025.
- The event explored compliance, digital change, patient voice and sustainability.
- Association leaders, healthcare professionals and suppliers engaged in fruitful collaboration.
- CCD offers scale, flexibility and sustainable operations.
- The city's culture and accessibility enhance networking and lasting connections.

From 1 to 3 October 2025, the Düsseldorf Convention hosted the ICCA Future of Healthcare Meetings at the Congress Centre Düsseldorf (CCD) on the Rhine. The event brought together association leaders, healthcare professionals and meeting suppliers who explored how medical meetings can remain relevant as clinical knowledge, regulations and audience expectations evolve. Focused on practical value, it combined meaningful content with purposeful networking.

A Destination that Matches Healthcare Ambition

Düsseldorf is a European hub for medical technology, pharmaceuticals and healthcare innovation. Its appeal for international meetings lies in a combination of practical advantages: a central location with high-speed rail links across Europe, an international airport with extensive connections and a venue ecosystem capable of supporting everything from specialised congresses to large exhibitions.

Hosting the 2025 event here highlights the city's commitment to stakeholder engagement, legacy and future-focused thinking. It also provides access to ICCA's education pathways, helping participants transform new ideas into better practice outcomes.

The city's character deepens the meeting experience. The Altstadt's brewery culture and cobblestone streets stand alongside the Gehry-designed MedienHafen and the Rhine Promenade, a mix of tradition and modernity that gives visitors a strong sense of place. From contemporary art at K21 Ständehaus to luxury shopping on Königsallee, Düsseldorf provides a cultural backdrop for informal exchanges that strengthen relationships beyond the meeting itself.

Why This Meeting Matters

The Future of Healthcare Meetings brings together association leaders, healthcare professionals and meeting suppliers to consider how medical gatherings should develop for the next generation. Since a significant share of international association meetings

Düsseldorf Congress

is linked to science and healthcare, the sector benefits from a platform where stakeholders can compare approaches, test ideas and shape shared understanding. The event fosters discussion on relevance and impact, going beyond logistics to focus on the purpose of uniting professionals to learn, collaborate and drive change.

For attendees, the value lies in both insight and access. The format brings association executives and ICCA Members into close contact, encouraging conversations that reveal challenges, opportunities and trade-offs. Previous editions have generated strong satisfaction, clear recommendations and broad international participation. The 2025 meeting builds on this by focusing on themes that directly relate to planning decisions, while also allowing time for connections that turn discussion into action.

The ICCA Community and Purpose

ICCA is a global community and knowledge hub for international association and governmental meetings. Its mission is to shape the future and importance of these gatherings, with workstreams covering leadership, advocacy, sustainability, legacy and inclusion. In Düsseldorf, this purpose is evident in how the event addresses challenges in healthcare meetings and connects them to practical tools, education and peer support. The focus is on providing reliable guidance in areas that influence quality and long-term value rather than fleeting trends. A shared agenda allows members to compare data, study case-based learning and agree on principles that are relevant across countries and specialties.

Advocacy lies at the heart of this approach. By involving destinations, venues, associations and industry partners, ICCA encourages alignment on what healthcare meetings should achieve for patients, professionals and communities. Legacy is an integral part of this alignment. Meetings that incorporate objectives, evaluate outcomes and share insights directly contribute to the broader health ecosystem, which remains a priority for both associations and hosts.

Who You Will Meet

The meeting is designed as an in-person gathering of healthcare association executives, ICCA Members and observers involved in healthcare meetings. Association leaders use the forum to refine services so their events remain relevant, sustainable and engaging. ICCA Members explore ways to support evolving requirements with venues, technology and destination services. Observers gain a clear understanding of how programme design and delivery are shifting in response to regulation, digital change and new audience needs.

> “The event fosters discussion on relevance and impact, going beyond logistics.”

Fully hosted places are available for associations by application, ensuring that essential voices are included.

Registered associations span clinical specialities and professional roles, reflecting the cross-cutting nature of the conversation. This diversity helps participants discover ideas that are adaptable across contexts, whether refining education, widening stakeholder engagement or testing new delivery models.

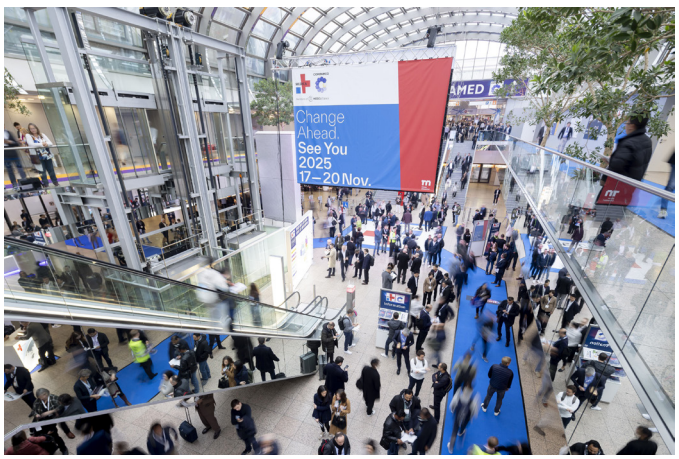
Themes That Keep Healthcare Meetings Relevant

The Düsseldorf content emphasises themes that shape near-term actions and long-term resilience. Compliance remains a key focus as pharmaceutical and device codes develop, influencing stakeholder engagement, sponsorship and programme design. Digital transformation continues to impact how professionals connect and learn, requiring formats that balance face-to-face depth with remote learning and broader community engagement.

The patient voice is increasingly central in meetings. Including lived experience aligns content with real-world outcomes and challenges assumptions about what makes education effective. Certification in CME and CPD adds a practical layer. As standards evolve, clear guidance on requirements and accreditation ensures programmes meet both regulatory and learner needs. Financial sustainability completes the picture, tying funding, partnerships and values together to build resilience when policy or industry involvement changes. Moderation across these themes ensures discussions remain focused and inclusive, with messages that planners can share with their teams.

A Venue Built for Scale, Flexibility and Delivery

The Congress Center Düsseldorf stands on the Messe Düsseldorf campus beside the Rhine, three kilometres from the airport and five kilometres from the Old Town. It links directly to adjoining exhibition halls, offering a flexible layout that can host up to 22,500 visitors. More than 10,000 square metres of exhibition space and 41 variable rooms allow smooth transitions between plenaries, workshops and networking. The campus as a whole provides 317,000 square metres of exhibition space, supporting events that combine science with industry presence. Across the city, around 15,000 hotel rooms in the three- to five-star range ensure ample capacity. Site upgrades continue, including



modernisation of Hall 9 and the North Entrance with a volume of around €200 million scheduled by 2028, plus a new ‘Messe Düsseldorf Cube’ headquarters to consolidate functions in a modern, sustainable building.

For organisers, the advantages are clear. The venue can shift to multiple formats within a single meeting, the campus supports efficient logistics, and the central location simplifies access to social and networking elements. Early planning is supported by clear venue details and direct contact points, allowing teams to align stakeholders with confidence.

> “Including lived experience aligns content with real-world outcomes and challenges assumptions.”

Sustainability That Supports Responsible Meetings

Sustainability is embedded in venue operations. Electricity is sourced from renewable providers. Kitchen waste, including cooking oil, is collected and sorted for compliant disposal. Cleaning relies on agents meeting Blue Angel and European Environmental Symbol standards. Visitors benefit from cycle parking, which encourages low-impact mobility. These measures give organisers concrete ways to integrate sustainability into event delivery.

At a city level, planning aligns with the United Nations Sustainable Development Goals and the 16 Steps Initiative for climate neutrality in events. Düsseldorf Convention integrates these frameworks into its own planning and advises partners on how to align corporate or association targets with on-site practices. For many organisers, the ability to document measures is as important as implementing them, making transparency a valuable asset.

Access at the Heart of Europe

Connectivity is one of Düsseldorf's strengths. Rheinbahn provides reliable local transport with buses, trams and the U-Bahn. Deutsche Bahn links Düsseldorf to the rest of Germany and Europe, placing Amsterdam and Brussels within two and a half hours, and Paris within four. These times make rail a realistic alternative to air for many European delegates.

Düsseldorf Airport (DUS) is one of Germany's largest international hubs and the main gateway to North Rhine-Westphalia. With nonstop flights by 60 airlines to nearly 50 countries, it connects the Rhine region to destinations across Europe and worldwide. Located only seven kilometres north of the city centre, the airport offers fast access to Düsseldorf's Old Town and Königsallee in about ten minutes by taxi or train.

The airport combines scale with convenience. Two on-site train stations and direct motorway links ensure smooth onward travel, while the central terminal connects piers A, B and C for easy navigation. Immigration and baggage claim are a short walk from arrival gates, and departures are equally streamlined. Passenger services include lounges, car rental and shopping, designed to make every journey comfortable and efficient.

Mobility That Powers Events

Behind every successful congress lies a seamless transport network, and mobility is an essential part of the delegate experience. RELAY Shuttle Services has built its reputation on making this possible, ensuring that thousands of participants can move smoothly between airports, hotels venues and social events.

With expertise in large-scale logistics and tailored VIP transfers, RELAY integrates transport planning into the fabric of an event. Route design, capacity management, contingency strategies and on-site coordination ensure that programmes run on time and stress-free. The company focuses on efficiency, comfort and sustainability, combining modern fleets with shared transfers that help reduce environmental impact.

Sponsoring the ICCA Future of Healthcare Meetings 2025 reflects RELAY's commitment to connecting people and enabling events. By positioning itself within a sector where mobility is vital, the company underlines its role as a trusted partner for organisers who want participants to arrive safely, punctually and ready to engage.

Technical Production That Elevates Delivery

Technical reliability is central to knowledge transfer in healthcare meetings. LLeyendecker eventsolutions brings more than 25 years of experience in full-service event technology with core expertise across Audio, Lighting, Video, Rigging, Kinetic and Design. The company supports organisers from concept to execution, starting with consultations and needs assessments, followed by detailed 3D event planning and coordinated on-site delivery across all technical areas. Modular

service models cover full-service production, dry hire for commercial customers, special constructions and partial services when clients handle other elements themselves.

For medical and scientific events, LLeyendecker prioritises speech intelligibility, reliable video transmission and secure hybrid participation. Teams support streaming, interactive tools and GDPR-compliant platforms so remote attendees can engage without compromising confidentiality. Investment in modern, energy-efficient technologies, optimised logistics and reusable materials supports sustainable production. With offices in Wuppertal and Berlin and operations worldwide, the company combines local roots with global reach to deliver precise, reliable and memorable events.

Hotel Partner for Healthcare Meetings

Healthcare meetings benefit from venues and teams that understand sector-specific requirements. With more than 1,250 hotels worldwide, Radisson Hotels provides dedicated Healthcare Meeting Solutions focused on compliance, efficiency, security and impact. The approach aligns with EFPIA and country-specific regulations, with unbundled rates and flexible billing to support transfer-of-value reporting and audit readiness. Delivery is discreet and professional with subtle signage and documentation. Teams are trained through Radisson Academy and selected properties are certified with Healthcare-Venues.com, supported on-site by healthcare champions who integrate each client's internal policies. Partnerships include collaboration with ICCA and consultants.

Coverage spans key healthcare hubs including France, the UK, Germany, Belgium and India. Many meeting spaces are equipped for hybrid participation with high-speed internet, advanced AV and flexible setups, and wellbeing is supported through calming spaces and healthy catering options. Every meeting and event space booked across EMEA has its carbon footprint automatically offset at no additional cost. The Healthcare Knowledge Exchange gathered representatives from more than 70 organisations in early 2025, produced 23 actionable solutions and achieved a 4.5/5 satisfaction rating, with the next edition scheduled in Florence on 2–3 March 2026.

> "The aim is to enhance the legacy of medical meetings by grounding them in compliance, education and lived experience."

A City Experience That Builds Relationships

Relationships often grow outside meeting rooms, and Düsseldorf's social fabric supports that. The Old Town's breweries provide informal spaces for conversation, while the Rhine Promenade offers a relaxed route for walks between sessions. K21 Ständehaus adds contemporary art and striking architecture to hosted gatherings. Local touches, from kiosks by the river to modern squares, make itineraries feel personal and memorable.

Networking formats benefit from this environment. When structured conversations are combined with a city that encourages exploration, introductions more easily

develop into meaningful exchanges. The long-term value appears in collaborations and projects that trace their origins to encounters in Düsseldorf.

What Düsseldorf Convention Brings

As Event Host, Düsseldorf Convention grounds the meeting in a destination that understands international association requirements and has the infrastructure to match them. Working with Düsseldorf Congress as Host Venue, the team links content with opportunities to discover the city, meet peers and make use of a venue designed for flexible formats. The host perspective emphasises the role of destinations and partners in content, community engagement and legacy. This approach helps delegates turn ideas into initiatives that involve local actors, from patient organisations to academic partners.

By bringing together healthcare association executives, ICCA Members and observers, the 2025 edition aims to turn discussion into action. Participants will gain clarity on compliance, practical direction on digital delivery, guidance on education standards and approaches to integrate the patient voice. They will leave with new contacts and a sharper view of how to build programmes that are financially sustainable and meaningful in impact.

Düsseldorf Convention invites the healthcare meetings community to three days of meaningful content, collaborative dialogue and valuable connections. The aim is to enhance the legacy of medical meetings by grounding them in compliance, education and lived experience, and by hosting them in a city and venue designed for impact.

Conflict of Interest

Spotlight articles are the sole opinion of the author(s), and they are part of the HealthManagement.org Corporate Engagement or Educational Community Programme.

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Cover Story

AI Applications: Can Radiology Take Inspiration from the Industrial Sector?

AI is transforming radiology, offering both interpretative and workflow-enhancing tools. Inspired by sectors like automotive, retail and finance, radiology can adopt AI-driven practices to improve efficiency, personalisation and cost control. From tailored reports to smart scheduling and inventory management, cross-industry innovations show great potential. Strategic adoption is vital as radiology navigates growing economic and competitive pressures.

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key points

- AI in radiology includes diagnostic tools and systems to optimise workflow and resource use.
- Other industries use AI for personalisation, automation and operational efficiency.
- Radiology can adopt AI practices from sectors like retail, finance and manufacturing.
- Customised reports and smart scheduling can improve patient experience and reduce delays.
- Strategic integration of AI is essential for radiology to remain competitive and cost-effective.

Public Perception of AI

Nowadays, artificial intelligence (AI) is widely used and has become a trendy buzzword to highlight technological products. Beyond this strong marketing appeal, AI is routinely used in our everyday lives. It enables self-driving features in vehicles, voice and facial recognition on smartphones and computers, fraud detection systems, automated trading tools and entertainment algorithms such as those used by social media platforms (Rodrigues et al. 2023). In the healthcare sector, AI promises major advancements, especially in medical imaging. In this discipline, interpretative AI solutions are used in clinical practice to detect or quantify anomalies. Such solutions have been widely studied and are the subject of numerous publications. Non-interpretative solutions, which focus more on optimising workflows and resources, are also emerging on the market (Tadavarthi et al. 2020).

With such a wide range of tools available, one may ask: is it truly feasible to integrate all these solutions into the day-to-day operations of medical imaging departments? Can the radiology field draw inspiration from other industries to optimise its workflows? This article aims to explore some possible avenues for reflection by extrapolating practices already implemented in sectors other than radiology.

Issue of AI for Radiology Institutes

As with previous technological innovations in medical imaging, the emergence of artificial intelligence marks a decisive turning point for radiology. However, unlike other industrial sectors, the implementation of AI in radiology has not yet been fully democratised nor adopted across all institutions. Yet the economic issues are substantial, especially in an increasingly competitive environment and under growing pressure to reduce costs.

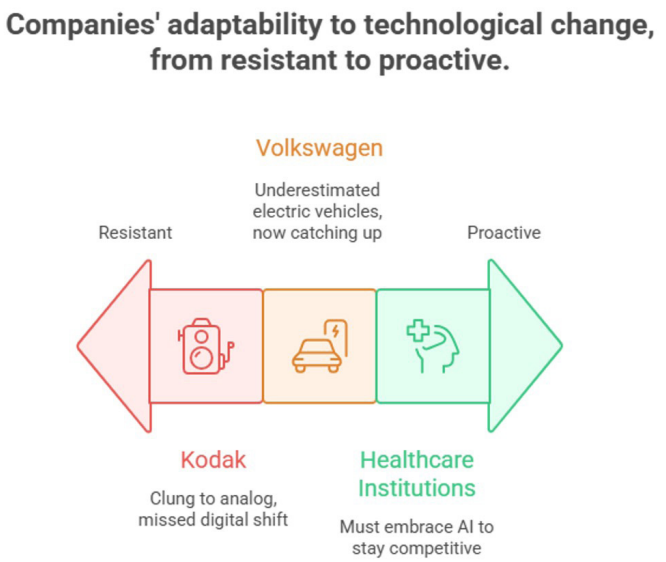

Figure 1. Corporate adaptation strategies across sectors in response to disruptive innovations and their associated outcomes. Source: Author's own work

The emergence of AI is driving major transformations in radiology not only in the profession itself, but also across the entire radiology ecosystem, with significant implications for the management and strategic direction of healthcare institutions. This strategic shift must be approached with discernment to avoid the fate of certain emblematic companies that failed to anticipate technological disruption and lost their competitive edge in a rapidly evolving market (Figure 1).

The case of Kodak is a particularly striking example of a poorly executed strategy. Once a pioneer in photography, the company remained overly committed to analogue film and failed to adapt to the digital era—ultimately disappearing in favour of more agile and forward-looking competitors (Tellier 2023).

A similar parallel can be drawn with Volkswagen, currently facing serious challenges after missing its transition to electrification. This lack of responsiveness and strategic foresight cost the company its position as a global leader. Once highly prosperous, Volkswagen is now confronting substantial financial pressures (Kehkasha Arora et al. 2024).

The Use of AI in Various Areas of Industry

Beyond its technological dimension which has already revolutionised many aspects of our daily lives, AI is driving major economic disruption, with an estimated global impact of more than €14.1 trillion ($15.7 trillion) by 2030. Of this, €5.9 trillion ($6.6 trillion) is expected to result from productivity gains, and €8.2 trillion ($9.1 trillion) from increased consumer demand for AI-enabled products and services (Rao & Verweij 2017).

Contrary to common belief, AI is already deeply embedded in our everyday lives (Figure 2). In the automotive sector, technologies such as autopilot systems, adaptive cruise control, distance monitoring and parking assistance are now standard in newer vehicle models and are all based on AI. In addition, AI-powered software can predict mechanical failures and help reduce traffic congestion. In retail, AI solutions enable product personalisation based on customer preferences, targeted advertising through machine learning algorithms and improved inventory management, thereby saving space and reducing costs. In the financial sector, AI is already firmly

> "The medical imaging sector must also draw inspiration from AI-driven innovations successfully implemented in other industries."

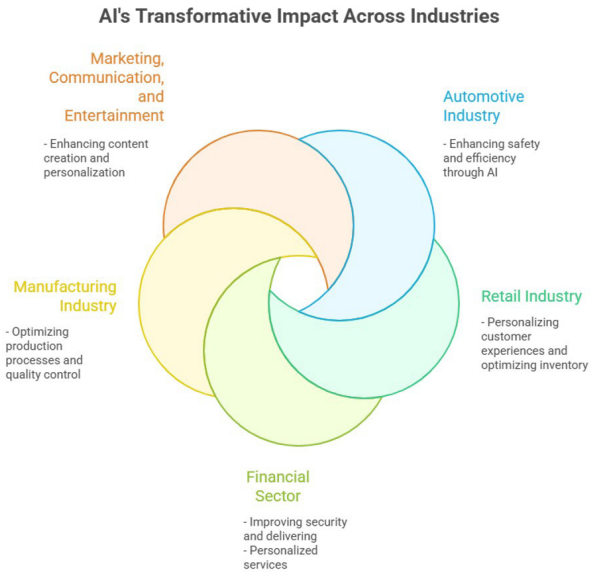

Figure 2. The use of AI solutions in various industry sectors. Source: Author's own work

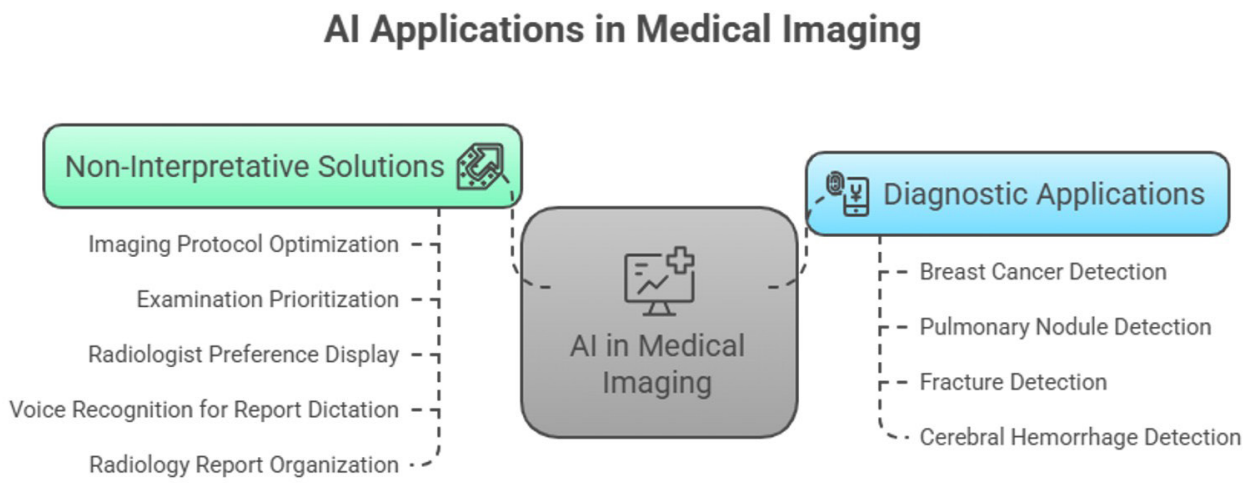

Figure 3. An overview of the various (non-exhaustive) applications of AI in medical imaging. Source: Author's own work

established. It is used to deliver personalised financial planning, detect fraud, identify money laundering schemes and automate various back-office processes. In manufacturing, AI applications can correct production line errors, optimise supply chains and enable on-demand production. These solutions lead to higher product quality and shorter delivery times for customers. Finally, in marketing, communication and entertainment, AI enhances content archiving and recommendation systems, supports content creation tailored to consumer preferences and enables personalised advertising. As a result, customers benefit from more relevant content and save time when searching for products or information.

> "AI applications can correct production line errors, optimise supply chains and enable on-demand production."

Application of AI in Medical Imaging

As discussed earlier, AI solutions applied to radiology (Figure 3) are primarily applied in diagnostic. Without being exhaustive, these include software for the detection of breast cancer, pulmonary nodules, fractures, cerebral haemorrhages and many others (Tadavarthi et al., 2020), while non-interpretative solutions focus on optimising workflow. Current software can adjust imaging protocols based on clinical demands (Brown & Marotta 2017), prioritise examinations according to urgency (Richardson 2021), display studies according to radiologists' preferences, use voice recognition to streamline report dictation (Lakhani et al. 2018) and organise and structure radiology reports (Syed & Zoga 2018).

The Potential of AI in Radiology

By taking inspiration from other sectors, it is possible to envision new AI-driven solutions aimed at further optimising workflow and reducing waiting times for both patients and referring physicians (Figure 4). For example, depending on the referring physician, an AI system could adapt the vocabulary and terminology used in radiology reports to make them more accessible. A report intended for a general practitioner should not appear overly technical, while one addressed to a specialist should avoid being overly simplistic. This approach mirrors the personalisation algorithms used in the entertainment industry, which tailor content to individual user profiles.

Drawing from the manufacturing sector, AI applications able of identifying delays in report validation and transcription could help to prevent disruptions in patient care. Similarly, inventory management solutions for contrast agents and consumables would help avoid overstocking costly items of interventional radiology such as biopsy

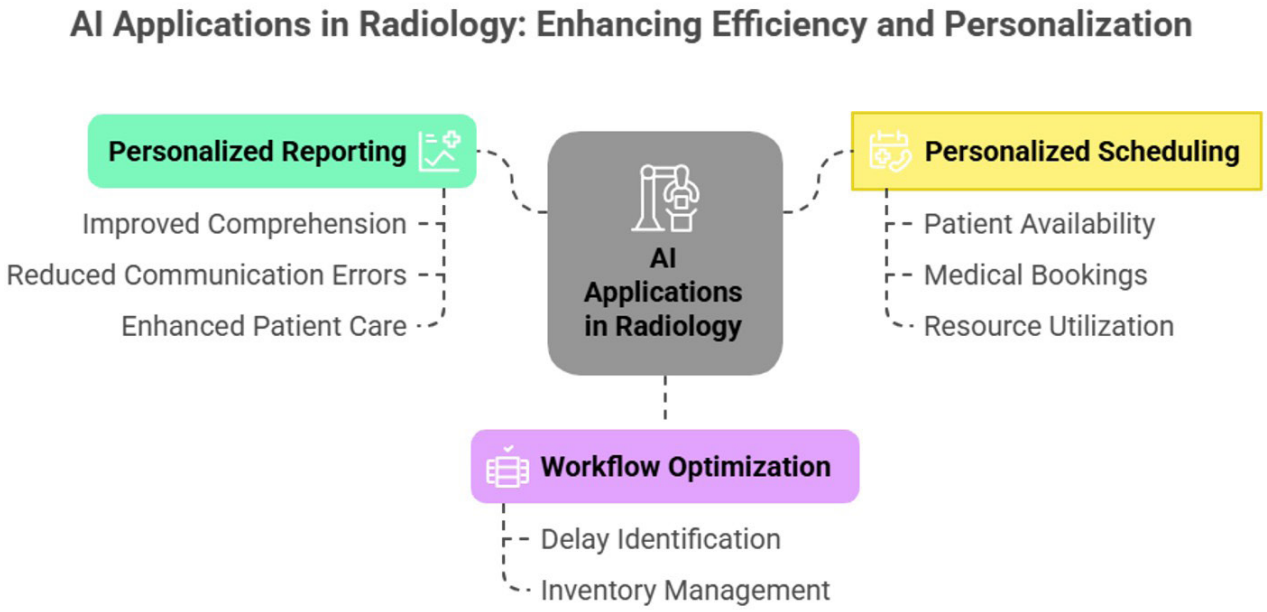

Figure 4. Potential avenues for AI development to better adapt to patient expectations and evolving healthcare trends. Source: Author's own work

needles, catheters, and trocars. Just as in the financial or retail sectors, AI could also be used to propose personalised appointment schedules based on a patient's availability and existing medical bookings within a clinic or hospital. Such systems would offer significant time savings for patients by minimising long wait times between consultations.

Conclusion

The field of radiology is undergoing profound transformation, particularly with the advent of AI, which is redefining both clinical practice and strategic management within imaging centres. This disruptive technology is already integrated into our daily lives with significant impacts on how we consume products and services. As in other industries, stakeholders and managers in radiology must not miss this turning point. They need to approach the transition to AI strategically and fully integrate it into both their clinical operations and organisational governance. In an increasingly competitive environment marked by economic pressures, the adoption of AI represents a critical challenge and a major opportunity for the future of radiology. To evolve, the medical imaging sector must also draw inspiration from AI-driven innovations successfully implemented in other industries.

Conflict of Interest

None

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NeuroGenAI: Transforming Personalised Medicine in Neurology

As part of the pre-project activities to build visibility (Phase 0 of impact maximisation), the project published the following article to gather feedback from the broad community of healthcare and IT experts on HealthManagement.org, which reaches 30,000 stakeholders and is supported by MindByte Communications.

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key points

- European consortium is building GenAI for personalised neurology care.
- Its framework centres on neurodegeneration, neuroinflammation and neuropsychiatry.
- It targets four uses: trajectories, synthetic data, digital twins and multimodal LLMs.
- A survey finds regulation, trust and privacy remain the main adoption barriers.
- The strategy prioritises explainability, federated data and engagement with EU policy.

Introduction

Neurological disorders are among the most urgent challenges today. In terms of years lived with disability (YLDs), they have already surpassed cancer and cardiovascular disease in Europe (Winkler et al. 2024), making them a top priority on the global health agenda. Over 300 million people worldwide are directly affected, and the economic and societal costs amount to hundreds of billions of euros each year. Alzheimer's disease alone is estimated to cost Europe more than €250 billion annually (European Brain Council n. d.), while the overall burden of neurological diseases, including Parkinson's, multiple sclerosis, and stroke, represents a significant portion of global healthcare expenditure. This burden is not just financial; it also profoundly impacts individuals' quality of life, affecting patients, families, and healthcare providers alike.

Against this backdrop, the emergence of generative artificial intelligence (GenAI) introduces a paradigm shift in how neurological diseases are understood, diagnosed, and treated. NeuroGenAI is an ambitious, multidisciplinary European research initiative designed to unlock this potential. Its mission is to develop the first foundational GenAI model and federated data space dedicated specifically to neurology and psychiatry. In doing so, NeuroGenAI aims to position Europe as a global leader in health innovation and personalised medicine, ensuring that technological progress is balanced with ethical oversight and clinical impact.

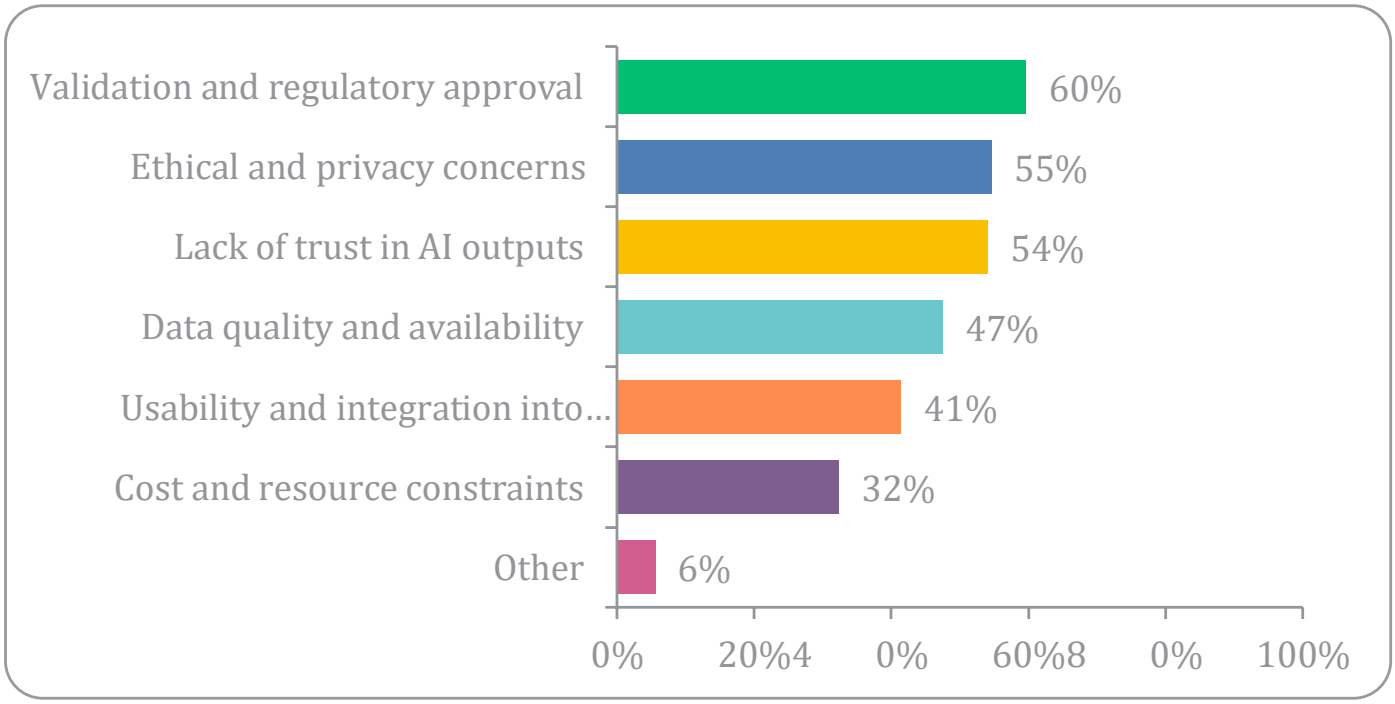

Figure 1. Major barriers to GenAI adoption in biomedical research and clinical practice

The NeuroGenAI Initiative

At its core, NeuroGenAI is a collaborative project that unites fifteen of Europe's most esteemed research centres, hospitals and brain institutes. Importantly, the initiative also extends beyond Europe, including clinical sites in America, Africa and Asia. This global scope ensures that models developed within the project are not restricted to a narrow patient demographic but are validated across diverse populations and healthcare systems. Such diversity improves generalisability and increases confidence in the reliability of AI-driven insights.

The project is structured around three main clinical pillars. The first concentrates on neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease and amyotrophic lateral sclerosis (ALS). Here, NeuroGenAI will employ personalised progression modelling to support earlier interventions and more precise treatment planning. The second pillar addresses neuroinflammatory and pain-related disorders, including multiple sclerosis and chronic headache syndromes, where digital twin technologies enable patient-specific simulations and more accurate response predictions. The third pillar focuses on neuropsychiatric and neurodevelopmental conditions, including attention deficit hyperactivity disorder (ADHD) and bipolar disorder, where explainable and bias-aware generative models can help navigate fragmented and heterogeneous data landscapes.

Within these pillars, four high-value use cases have been prioritised:

- Disease trajectory simulation in neurodegenerative disorders using multimodal longitudinal data.
- Synthetic data generation for low-resource or sensitive domains to safeguard privacy whilst enhancing model training.
- Digital twin–based in silico clinical trials for multiple sclerosis and bipolar disorder.
- Multimodal data interpretation where large language models integrate imaging data with unstructured text for more cohesive decision-making.

By addressing these use cases, NeuroGenAI is establishing a versatile and scalable foundation for transforming patient care. Its goal is not only to develop new algorithms, but also to design systems capable of implementation in real-world hospital environments, improving diagnostic speed and accuracy, and enabling clinicians to personalise treatments with greater confidence.

Survey Insights: Understanding Stakeholder Perspectives

Before starting full-scale development, NeuroGenAI carried out a comprehensive survey to better understand the opportunities, challenges and expectations related to the use of generative AI in neurology. The survey invited 10,000

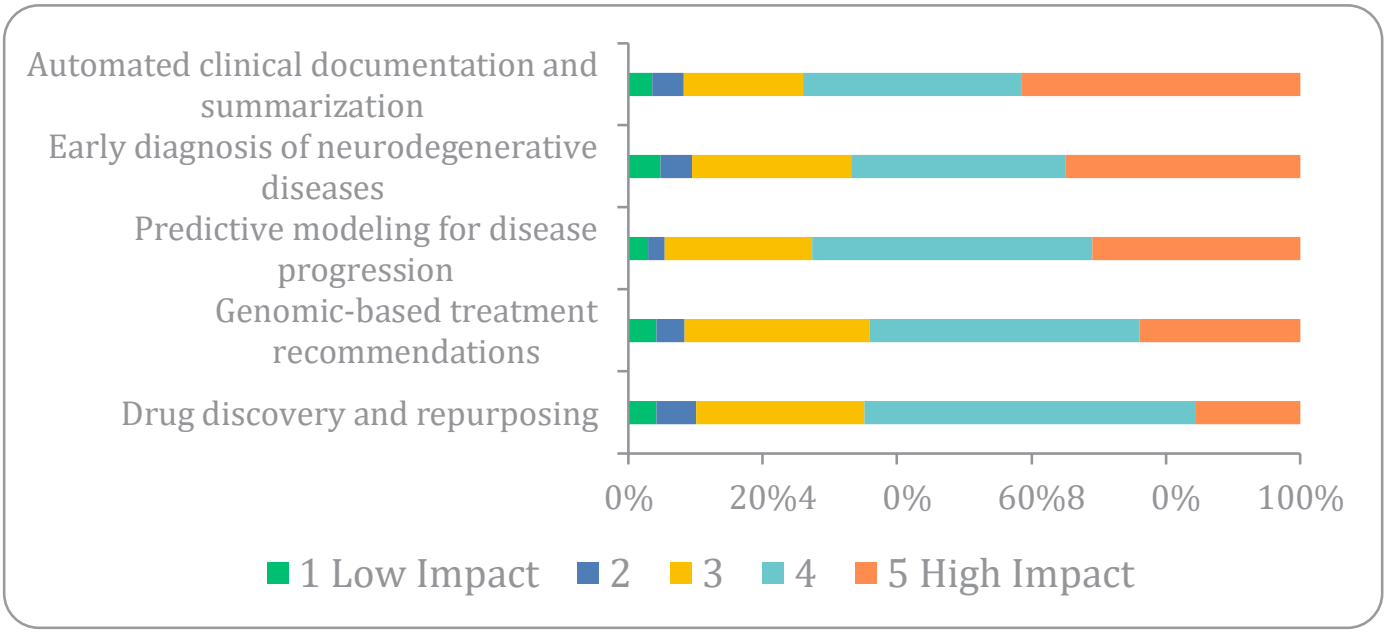

Figure 2. Potential impact of GenAI in neurology use cases

stakeholders, including clinicians, researchers, policymakers and technology experts. Of these, 198 completed the survey, offering a valuable range of perspectives that continue to influence the project's direction.

Major Barriers to Adoption

The survey found that regulatory approval is seen as the biggest obstacle to adoption, mentioned by 60% of respondents. Concerns about trust in AI outputs (54%) and ethical and privacy issues (54%) also ranked highly. These results highlight the need to align AI initiatives with transparent regulatory frameworks and to build trust through clearly demonstrated safe, explainable and ethical practices.

Opportunities in Neurology

When asked to identify areas with the greatest potential, respondents highlighted clinical documentation, early diagnosis and drug discovery. These are fields where GenAI can deliver immediate and transformative benefits:

- Automating clinical documentation could reduce administrative tasks, freeing up to 20% of physicians' time each week, according to OECD benchmarks.
- Early diagnosis, especially in Alzheimer's and Parkinson's, could add years of healthy living by enabling earlier interventions.
- Drug discovery aided by synthetic data and molecular modelling could reduce the typical 10–15 year development cycle by several years.

Integration Challenges

The survey also highlighted the practical challenges of integrating multimodal data, especially imaging, genomics and electronic health records (EHRs). Two-thirds of respondents identified data standardisation as a key difficulty, while over half mentioned the problem of missing or incomplete datasets. This underscores the urgent need for federated data infrastructures and harmonisation strategies, which are central to the NeuroGenAI design.

Explainability and Stakeholder Engagement

- Eighty-one percent of respondents emphasised that explainability is highly important in GenAI systems designed for clinical use.
- Seventy-nine percent highlighted the necessity for strong stakeholder engagement throughout all stages of development and validation, particularly in ethical governance.

From Survey to Strategy

The survey results were seen not just as background data but as a foundation for action. The NeuroGenAI strategy directly addresses stakeholders' concerns and expectations. Trust and explainability are built into the model design from the outset, with deliberate investment in frameworks for bias detection and transparent reasoning. Challenges related to data quality and integration are handled through federated data spaces that comply with privacy regulations while reducing fragmentation.

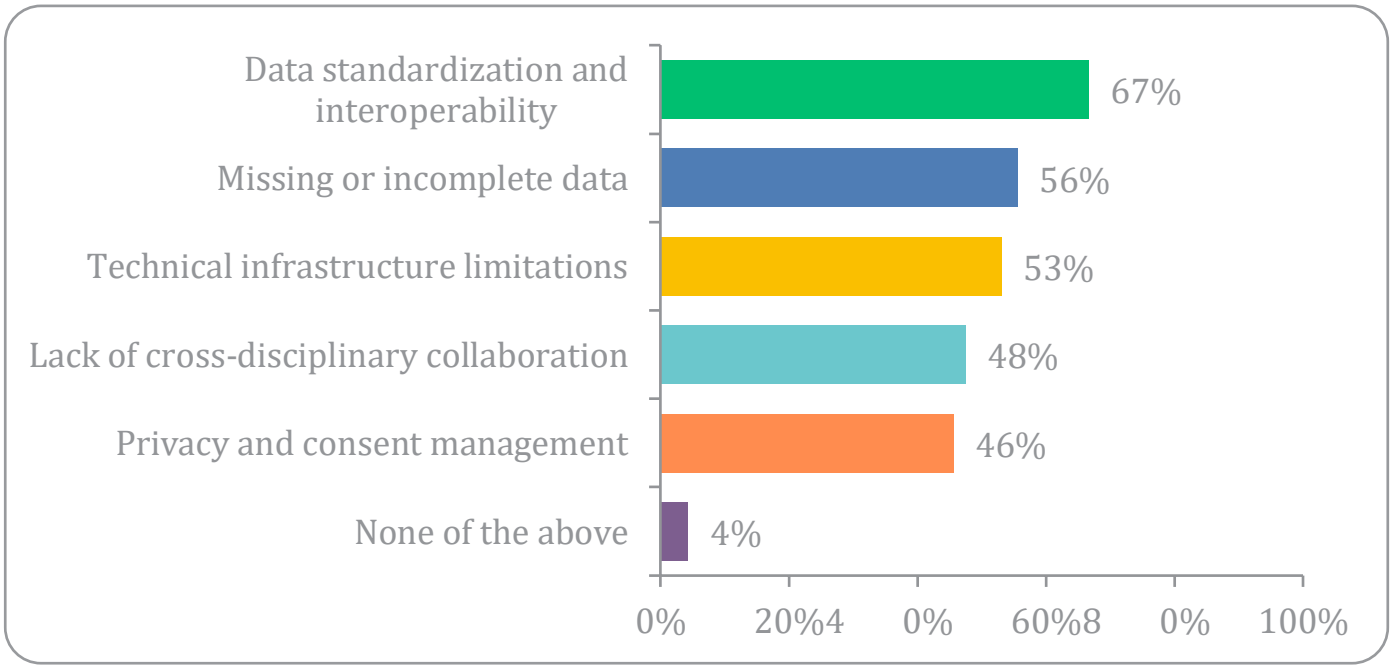

Figure 3. Challenges to integrating multimodal data

Regulatory hurdles are proactively managed through engagement with the European Medicines Agency (EMA) and policymakers responsible for the AI Act and medical device regulation. Stakeholder involvement is formalised, with governance structures ensuring that patients, clinicians, researchers and policymakers stay central to the initiative rather than just observers.

Health System Implications

For clinicians, the implications are immediate and practical. Generative AI tools developed through NeuroGenAI will assist in earlier diagnosis, providing more precise trajectories for conditions such as Parkinson's or multiple sclerosis. They will also support personalised treatment recommendations that adapt over time, aligning with patient-specific data rather than broad generalisations. In Alzheimer's disease, for example, AI systems could combine imaging, speech pattern analysis and genetic data to predict progression years in advance, offering clinicians a window of opportunity for earlier intervention.

Hospitals and healthcare organisations will benefit from reduced inefficiencies, particularly in clinical trials and documentation. Digital twin simulations could decrease recruitment costs and shorten trial timelines by up to 30%, based on prior experience with oncology AI trials. Automated documentation systems may free clinicians to spend more time with patients, improving both satisfaction and outcomes. For health systems under strain, these efficiencies translate into tangible cost savings and enhanced patient flow.

Patients themselves stand to gain the most significantly. With models trained on diverse, multimodal datasets, they will receive more precise diagnoses, more personalised treatments and ultimately a better quality of life. Significantly, AI-generated synthetic data can facilitate research into rare conditions like ALS, which often suffer from limited available data. This means patients with rare diseases will no longer be excluded from AI benefits simply because of small datasets. Meanwhile, policymakers and payers will have stronger evidence to inform funding decisions and long-term health planning. If AI systems demonstrate improved outcomes at lower costs, they will support stronger arguments for reimbursement and investment in digital health infrastructure. Health economics becomes central to the value proposition of NeuroGenAI, offering potential reductions in disability-adjusted life years (DALYs) and related economic losses.

Global Positioning: Europe as a Leader

One of NeuroGenAI's key features is its European identity. Although the United States and China are also making rapid advancements in AI for healthcare, Europe

has chosen a path that prioritises ethics, transparency and inclusivity. By embedding these values into the very foundation of its AI models, NeuroGenAI helps the European Union not only to compete technologically but also to set global standards. In doing so, Europe can shape international benchmarks for trustworthy AI, influencing not just how the technology is used within its own borders but worldwide.

The inclusion of clinical sites outside Europe bolsters this leadership role. By testing models in America, Africa and Asia, NeuroGenAI ensures that its tools are relevant beyond a European patient base, making them more robust and globally influential. This international validation enhances credibility and strengthens the EU's position as a leader in responsible AI globally.

> "Its mission is to develop the first foundational GenAI model and federated data space dedicated specifically to neurology and psychiatry."

Comparisons highlight Europe's unique role. In the US, private industry leads development, often outpacing regulatory adaptation. In China, government-led initiatives focus on centralisation and scale, sometimes raising concerns about transparency. Europe, however, bases its competitiveness on trust, ethics and patient inclusion. For international stakeholders, this approach increases reliability and encourages collaboration.

Future Outlook

Looking ahead, the potential of multimodal generative models in neurology is vast. Over the next five to ten years, we can anticipate systems that:

- Integrate real-time wearable data with hospital records for continuous monitoring.
- Support prevention by recognising risk profiles years before symptoms emerge.
- Foster cross-sector collaboration between pharma, biotech and healthcare providers to accelerate therapy development.
- Train clinicians to utilise AI tools effectively, with curricula combining medical expertise and digital literacy. Incorporating these advancements into clinical practice could lead to a significant shift in how neurological disorders are managed worldwide within the next decade.

Conclusion

Generative AI has the potential to revolutionise neurology by creating new opportunities for diagnosis, modelling and treatment. NeuroGenAI shows how Europe can responsibly use this technology by incorporating trust, explainability and ethical governance at every development stage. Supported by survey insights, clinical expertise and international collaboration, it is not just a research project but also a blueprint for the future of personalised medicine in neurology.

As the burden of neurological disease continues to grow, the significance of NeuroGenAI becomes even more vital. By advancing scientific understanding and clinical practice, and by addressing the concerns of regulators, clinicians and patients, it represents a vital step towards a healthcare system that is more precise, more efficient, and above all, more compassionate.

Disclaimer

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Hospitals of the Future: The Next Frontier in Patient-Centred Care

Hospitals are rapidly evolving into smart, connected ecosystems focused on proactive, personalised care. Leveraging AI, robotics, remote monitoring and digital health tools, they enhance diagnostics, improve workflows and support decentralised models like virtual wards. Predictive analytics, interoperable data systems and sustainable infrastructure further enable this shift, despite integration hurdles, workforce shortages and cybersecurity concerns.

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key points

- Hospitals are adopting AI and robotics to deliver faster, more accurate care.
- Remote monitoring and virtual wards support decentralised care delivery.
- Predictive analytics help identify health risks before symptoms appear.
- Interoperable data systems enable coordinated, personalised treatment.
- Challenges include tech integration, data security and funding limitations.

Healthcare Delivery Amid Transformation

Healthcare is undergoing a profound transformation due to a powerful convergence of demographic and epidemiological changes. A rapidly ageing population, the surge in chronic and lifestyle-related illnesses – these shifting epidemiological patterns are placing new demands on health systems. Simultaneously, breakthroughs in digital health and artificial intelligence, combined with the need for value-based care and economic pressure of unsustainable costs, are redefining how healthcare is financed, accessed and delivered. At the same time, patients are no longer passive recipients; they are informed, empowered consumers who demand convenience, transparency and personalisation. This rising tide of healthcare consumerism forces hospitals to evolve beyond their traditional roles.

Once characterised by centralised, paper-based and reactive care models, hospitals now face unprecedented pressure to modernise. Mounting financial strain, workforce shortages and siloed infrastructures are pushing healthcare institutions to rethink, redesign and reimagine care delivery for a new era.

Hospitals are under pressure to cut costs while improving outcomes as healthcare costs continue to soar. Chronic disease is at an all-time high. According to the World Health Organisation's 2024 report, in 2021, noncommunicable diseases (NCDs) were responsible for 75% of non-pandemic-related deaths globally (43 million people). WHO predicts this trend to continue: by around 2050, diseases such as cardiovascular diseases, cancer, diabetes and respiratory illnesses will account for 86% of the 90 million deaths each year (WHO 2023).

Amongst these staggering numbers, there is a critical gap between the need and the supply of healthcare workers. WHO estimates a shortage of 11 million health workers by 2030, mostly in low- and lower-middle-income countries (WHO n.d.). This paradigm shift is compelling hospitals to embrace decentralised, technology-enabled, interoperable systems that deliver proactive, personalised and value-based care.

The Rise of Smart Hospitals: Trends and Technologies to Watch

Demand for Proactive and Precision Care

Advanced diagnostics, medical imaging and digital transformation are pivotal to delivering proactive, personalised care in the modern hospital setting.

Genomic testing is essential for delivering precision care in hospitals by providing critical insights into how a patient's unique genetic makeup influences disease risk, diagnosis, prognosis and treatment response. In August 2024, Scientists at St. Jude Children's Research Hospital developed a cost-effective genomic panel that diagnoses over 90% of paediatric cancers by sequencing just 0.15% of the genome, enabling precise classification and personalised treatment.

Many hospitals are partnering with **non-invasive liquid biopsies** for the convenient and precise screening of patients. For example, Guardant Health, Inc. has entered a partnership with one of Europe's leading cancer research organisations – Vall d'Hebron Institute of Oncology (VHIO) to establish in-house liquid biopsy testing services, using Guardant Health's industry-leading proprietary digital sequencing platform, at VHIO's facility in Barcelona, Spain. This will enable earlier, faster and more accurate diagnosis, therapy selection and monitoring.

Artificial Intelligence (AI) and **machine learning** (ML) algorithms transform diagnostics by analysing medical images, pathology slides and clinical data with speed and accuracy that often surpass human capabilities. Forward-thinking hospitals are investing in advanced infrastructure to harness these technologies for faster, more reliable diagnosis and improved patient outcomes. In January 2025, the Mayo Clinic launched its Mayo Clinic Digital Pathology to accelerate diagnosis. One of the most prominent trends in healthcare today is hospitals partnering with technology developers to enhance patient care through **innovation and digital solutions**. In June 2025, integrated health system Sutter Health in California, US, formed a strategic partnership with Aidoc to use Aidoc's real-time AI operating system (aiOS™) across Sutter's comprehensive care system, enabling early identification and faster care implementation.

> "Soon, hospitals will be fully predictive, hyper-personalised, autonomous and seamlessly connected."

Digital technologies enable real-time data collection, personalised communication and targeted care. By integrating EHRs with data from clinicians, labs, devices and wearables, smart hospitals gain a holistic view of each patient. Remote monitoring and IoT tools such as wearables are vital in delivering proactive, personalised care across hospital settings. For example, Zio cardiac monitoring patch by iRhythm Technologies (California, US) is used in several hospitals including Spire Claremont Hospital and Hospital of St. John's & St. Elizabeth in the UK, as well as Brigham and Women's Faulkner Hospital in Boston, Massachusetts, US. They are used in emergency departments (EDs) and high-risk patients (symptomatic and asymptomatic patients) to diagnose arrhythmias remotely.

Clinical Decision Support Systems (CDSS) in hospitals provide real-time, evidence-based recommendations using patient data and clinical guidelines. They help prevent adverse drug

interactions and missed preventive care opportunities. CDSS also enable personalised care by tailoring interventions to individual factors such as age, gender and genetic profile. CDSS is a rapidly expanding market, with companies like Philips and Siemens offering proprietary platforms.

> "Patients have evolved into active, informed participants in their health journeys."

Soon, hospitals will be fully predictive, hyper-personalised, autonomous and seamlessly connected. Predictive AI will analyse vitals, genomics, lifestyle and environmental data to detect diseases before symptoms emerge. Another transformative technology is the digital twin, which creates a virtual replica of a patient's body to simulate treatment responses. This will help physicians choose interventions such as medications, surgeries and lifestyle changes and avoid adverse outcomes.

Automated and Intelligent Infrastructure

Automated hospital infrastructure integrates intelligent systems to optimise healthcare operations, reduce human error and enhance patient outcomes.

The **Internet of Things** (IoT) is a cornerstone of smart hospital infrastructure, enabling seamless data exchange, real-time monitoring and automation. Integrating wearables, smart beds or fall detection systems can help transform the care facility into a connected ecosystem. For example, Baxter-Hillrom's Centrella™ Smart+ Bed can monitor the patient, alert the nurse and detect improper positioning in bed. This is used in major health systems like Mount Sinai Health System, the Cleveland Clinic and many others.

Hospital service robots are increasingly used to automate routine operational tasks, such as delivering meals, medications and lab samples, reducing human error and freeing up staff to focus on critical patient care. Autonomous Mobile Robots (AMRs) are now widely deployed for logistics, disinfection and pharmacy dispensing, significantly enhancing efficiency across hospital operations. UV-light disinfection robots, for example, sanitise patient rooms between uses, helping to lower hospital-acquired infection rates.

In recent years, these service and logistics robots have seen rapid adoption, becoming integral to the modern hospital ecosystem. For example, the Xenex LightStrike® Disinfection Robot with pulsed xenon UV light technology is used in over 1000 hospitals across five continents. In 2021, the European Commission financed the deployment of 200 UVD disinfection robots (by Blue Ocean Robotics, Denmark) in hospitals across Europe. Rising morbidity and mortality from hospital-acquired and antibiotic-resistant infections are expected to accelerate the future adoption of advanced infection control technologies. The future lies in developing robots that are not just autonomous, but also intuitive, adaptive and seamlessly collaborative, transforming them into true partners in care delivery.

To address the growing shortage of healthcare workers in hospitals, **Robotic Process Automation** (RPA) offers a powerful solution by automating administrative tasks such as billing, claims processing, patient registration and data entry, as well as streamlining supply chain functions like inventory management, procurement and vendor coordination. For example, Mid Yorkshire Hospital National Health Service (NHS) Trust found that using RPA to automate the registration process saved 72% of the time taken to register new staff for e-learning.

AI plays a vital role in intelligently controlling the hospital infrastructure, such as AI-controlled smart patient rooms, intelligent bed management and staffing optimisation. AI integration in robots improves autonomy in decision-making, navigation and human-robot interaction. Innovations like **natural language processing (NLP)** make robot interactions more human-like. Edge computing reduces latency, improves response time and saves bandwidth by processing data locally or near the network's edge. Example in Baltimore, US- John Hopkins has a Judy Reitz Capacity Command Center which uses AI to autonomously manage and coordinate hospital staff, beds and systems. This has led to an 83% reduction in operating room holds, a 38% improvement in bed assignment time and a 46% increase in complex transfers.

Modernisation of operating theatres includes surgical robots, advanced visualisation technologies (augmented and virtual reality-based surgery

visualisation, 3D imaging) and digital integration across the systems. Surgical robots provide better control and precision for very complex and delicate surgery. Robot-assisted surgery requires smaller incisions, leading to less trauma, less blood loss, reduced complications, faster recovery, improved patient outcomes and shorter hospital stays. This long-term savings from reduced complications and hospital stays attracts hospitals offering value-based care to the patients.

Institutions must also build or upgrade robotic surgery training labs and simulation centres for surgeon onboarding and credentialing.

Decentralised Care Delivery

The hospitals have always been a centralised care delivery model; however, decentralisation makes it more distributed and accessible, ensuring care continuity. The hospitals are integrating remote services and decision-making to reduce the hospital load and enhance chronic disease management through regular touchpoints. High-risk patients are often a part of the virtual ward, where, post-hospitalisation, they are monitored and treated at home or in community settings, using remote monitoring tools, telemedicine and digital care coordination platforms. For example, the Netherlands-based Luscii is an intelligent remote monitoring and care platform. Several Dutch hospitals and NHS Trusts use it in the UK.

Telepresence robots are an integral part of virtual ward ecosystems, enabling remote clinical teams to interact with patients in a more immersive, real-time and humanised way. They enhance the traditional remote monitoring approach by adding mobility, visual presence and bi-directional communication, extending the hospital's reach into the patient's home or care setting.

Telepresence robots enable decentralised care in hospitals. They can be used by off-site specialists (eg neurologists and cardiologists) to visit patients virtually, doctors can perform rounds across multiple wards without being physically present, and surgeons can consult on procedures remotely using the robot's camera. InTouch Vita, also known as the RP-Vita, by Teladoc (InTouch), is one of the common telepresence robots used in several hospitals across the US.

In a hospital setting, **point-of-care diagnostics** and **mobile imaging devices** decentralise care delivery by bringing diagnostics closer to the patient, rather than requiring patients to be moved through centralised departments. They are used mostly in critical or emergency care to speed up diagnosis or decision-making. For example, Siemens' Atellica® VTLi Patient-side Immunoassay Analyser (to detect high-sensitivity troponin I) or RAPIDPoint® 500e Blood Gas System are used in EDs to minimise patient overcrowding and waiting time.

Mobile imaging devices — including mobile X-ray systems (GE Healthcare AMX Navigate, Siemens Mobilett Elara Max), handheld or portable ultrasound (Butterfly Network Butterfly iQ+, Philips Lumify, GE Vscan Air), mobile CT scanners (Siemens SOMATOM On.site) and mobile MRI units (Hyperfine Swoop MRI) — enhance patient safety by reducing the need to transport critically ill or immobile patients from intensive care units (ICUs) or emergency departments (EDs) to imaging centres. These devices enable bedside imaging, allowing faster diagnosis.

> "The future lies in developing robots that are not just autonomous, but also intuitive, adaptive and seamlessly collaborative."

Empowered Patient and Health Partners

This age of the internet has fundamentally reshaped the role of patients in the healthcare system. They are no longer passive care recipients; patients have evolved into active, informed participants in their health journeys. Hospitals with self-service kiosks or in-room tablets allow patients to interactively check in, review treatment plans or learn about their condition. Hospital-integrated **virtual assistants or conversational AI** provide 24/7 support for basic health concerns and help patients with symptom checking, medication guidance or post-discharge queries. For example, Florence chatbot provides automated clinical conversations via text, providing medication reminders and appointment help to NHS patients.

Secure web-based platforms, or mobile apps that give patients access to their health records, lab results, prescriptions and appointment schedules. Virtual care systems offer real-time access to doctors, therapists and other providers via video or chat.

Some hospitals focus on holistic wellness and introduce **digital interventions or gamified behavioural apps** to manage chronic conditions or mental health through treatment journeys. In India, Medicover Hospitals has partnered with Lupin Limited (Lupin) to use Lupin Digital Health's advanced digital therapeutics platform to provide at-home rehabilitation to Medicover's cardiac patients, thereby improving post-operative rehabilitation and care. This digital therapeutic platform will support patients through remote monitoring and treatment adherence post-discharge.

Predictive Care

Hospitals offer predictive care by integrating advanced data analytics, AI-based diagnosis and real-time monitoring technologies to deliver tailored treatments and anticipate future health risks. CDSSs with predictive analytics help forecast potential clinical events, disease progression, health risks, early detection, targeted intervention and personalised prevention strategies. These technologies have a high impact on EDs and ICUs, where timely decisions are crucial.

AI-based triage tools predict which patients are high-risk, monitor ECG, troponin levels and patient history to predict myocardial infarction risk, monitor real-time vitals, labs and symptoms to flag sepsis risk up to 48 hours in advance, predict ventilation weaning prognosis and acute kidney injury risk. In February 2025, Stanford Medicine received FDA clearance on its ML-based predictive sepsis test. Several other hospitals have developed internal predictive alarm systems, like Mayo Clinic's AWARE (Ambient Warning and Response Evaluation) or John Hopkins' TREWS (Targeted Real-time Early Warning System).

Secure Interoperable Health Data Ecosystem

Interoperable platforms can help facilitate real-time data sharing across departments, hospitals or care settings, breaking down information silos for coordinated, personalised care. A secure and interoperable health data ecosystem is essential for patient-centric, precise and predictive care. This requires adopting FHIR (Fast Healthcare Interoperability Resources) for API-based data sharing, HL7 v2/v3 for messaging between systems, and end-to-end encryption for data in transit and at rest.

A standout example of an interoperable hospital system with strong collaboration is the Carequality–CommonWell Alliance, which enables nationwide health data exchange across competing hospital networks, EHR systems and care settings in the United States. Europe's secure and interoperable health data ecosystem is anchored by the European Health Data Space (EHDS) and strong privacy legislation (GDPR). This EHDS, launched in 2022 by the European Commission, aims to enable secure, cross-border access and health data exchange across EU member states. It empowers citizens to control their electronic health records while supporting clinical care and for secondary uses like research and innovation.

Smart Sustainable Hospitals

Beyond enhancing clinical efficiency and patient care, future hospitals are focused on minimising environmental impact and optimising resource use. This is through Smart Building Management Systems (BMS), which automate control of lighting, HVAC, water and energy systems, and deploy solar panels, geothermal systems and energy storage solutions. AI can optimise energy usage, predict failures and streamline logistics. For example, Erasmus Medical Center, Netherlands, is energy efficient using thermal energy storage and solar panels and has an intelligent lighting system with motion-sensor technology to adjust based on occupancy and daylight automatically. It uses AI and IoT-based building management systems to optimise temperature, airflow and humidity in real time.

Transition to Smart Hospitals: Need to Overcome Challenges

Data Privacy and Security. As healthcare systems become more interconnected through electronic health records (EHRs), wearables, AI tools and remote monitoring, the volume, sensitivity and vulnerability of patient data also increase. Hospitals should add data privacy and security controls to every digital infrastructure layer. Federated and consent-driven data sharing should be used, with multi-factor authentication. The clinical and administrative staff should be regularly trained on data handling, phishing threats, device hygiene and compliance protocols.

Technology Integration Challenges. Many hospitals rely on outdated systems that do not support integration with modern digital or robotic technologies. Upfront investment in hardware and software may be difficult for smaller hospitals or rural facilities. Even the larger hospitals' leadership may hesitate to invest without a clear return on investment. Physicians, nurses and administrative staff may trust in new technologies or may not be well trained in these new tools. These new tools can interrupt established clinical workflows, adding to the clinical load.

Legacy systems can be modernised with APIs, middleware and HL7 FHIR standards. Cloud platforms

can also be used to support scalability and flexibility. Balancing cost with long-term value through phased investments, leveraging public-private partnerships, grants and digital health innovation funds can be ways to invest in upgrading the hospital infrastructure.

Our Perspectives on Way Ahead

Technology-hospital partnership. Hospitals must strategically collaborate with technology partners who align with their clinical and operational ambitions, reducing readmissions, enhancing efficiency or expanding access to care. Beyond tech alliances, hospitals can amplify innovation by partnering with academic institutions, incubators and peer health systems, creating ecosystems of shared knowledge, co-development and continuous learning. By embracing this collaborative innovation model, hospitals position themselves not just as providers of care but as architects of the future health system.

Digital Transformation. To keep pace with the modern healthcare demands, hospitals must embrace digital transformation as a strategic imperative. Beyond integrating wearables, IoT devices, apps, portals or decision support systems, there should be data-sharing through interoperable platforms across departments and institutions, which improves coordination.

Virtual front doors. Hospitals should have patient-centric digital front doors, such as patient portals, mobile apps and chatbots, for 24/7 omnichannel engagement and to empower patients throughout their care journey.

Future-ready smart hospitals will not just treat illness but will champion proactive, holistic wellness, delivering seamless, precise and patient-centric care.

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Conflict of Interests

None.

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The Smart Hospital Maturity Model: Paving the Way for Healthcare's Digital Future

The Smart Hospital Maturity Model offers a framework to guide healthcare organisations through digital transformation. It defines six stages of smart hospital development, highlights trends like AI-driven revenue cycle management and data storage challenges, and stresses the importance of analytics maturity. By adopting SHMM, hospitals can systematically advance toward fully integrated, patient-centred smart care.

STEPHEN LIEBER

Chief Executive Officer | Alliance for Smart Healthcare Excellence | Washington DC, USA

key points

- The Smart Hospital Maturity Model provides a framework for healthcare digitalisation.
- Hospitals progress through six stages toward full smart technology utilisation.
- AI is transforming revenue cycle management, boosting efficiency and reducing errors.
- Data storage demands are rising sharply, requiring strategic upgrades and planning.
- Advanced analytics adoption is critical for personalised, efficient and predictive care.

Healthcare is undergoing a profound digital transformation, driven by the convergence of advanced technologies, data analytics and patient-centric care models. In an era of rapid technological advancement, hospitals strive to become more efficient, patient-focused and technologically integrated. To guide healthcare organisations through this evolution, the Smart Hospital Maturity Model (SHMM) provides a structured framework, helping them assess their current capabilities and plot a strategic course toward becoming fully "smart" hospitals.

Building the Foundation: Smart Care Technologies and Processes

Smart healthcare refers to the utilisation of advanced technologies, data analytics and connected systems to improve healthcare delivery efficiency and patient outcomes. A growing trend in healthcare is the increased adoption of smart care technologies and processes. These technologies include Internet of Things (IoT) medical devices, AI, big data analytics, mobile and virtual health applications, as well as remote and ambient patient monitoring and communication systems.

Key applications of smart care encompass a wide range of technologies and functionalities designed to enhance both clinical and operational performance. These include advanced analytics for extracting actionable insights from large datasets; real-time and ambient patient sensing and monitoring systems that continuously collect vital information; and automated diagnostics and clinical decision support tools that assist healthcare professionals in making timely and accurate decisions. Personalised medicine, leveraging genomic data and patient-specific information, enables tailored treatment strategies, while multiple application-integrated platforms ensure seamless connectivity and interoperability across different systems.

In practical terms, example implementations of these applications include patient sensors and wearable devices that monitor health indicators continuously, AI-powered tools that assist in clinical evaluations and automated medication management systems that ensure accurate dispensing and reduce human error. Real-time staff and patient identification technologies enhance security and operational flow, while real-time business functions such as insurance validation and materials management streamline administrative processes. Virtual care delivery through command centres integrates multiple applications to offer remote consultations, monitor patient status and manage resources efficiently, reflecting the growing emphasis on decentralised and patient-centred healthcare models.

> "Unlocking the full potential of data transformation is critical for healthcare providers to position themselves as truly 'smart' hospitals."

The Six Stages of Smart Hospital Development

The SHMM, developed by the Alliance for Smart Healthcare Excellence with support from care.ai (now part of Stryker), evaluates healthcare providers across three dimensions: people, places and processes. Over 560 data points from an 89-question survey drive the scoring of the SHMM. Participants are placed in one of six stages, each reflecting a higher level of technological integration and operational sophistication:

- **Leap 0 (Unassisted Processes):** Basic IT infrastructure is in place, with limited digital integration and reliance on manual workflows.
- **Leap 1 (Point Solutions):** Hospitals use disjointed digital solutions to assist with specific tasks but lack a coordinated smart care strategy.
- **Leap 2 (Functional Platforms):** Integrated and interoperable networks emerge, with IoT devices like smart beds and connected medical equipment supporting care.
- **Leap 3 (Integrated Systems):** Cross-functional integration becomes prevalent, smart care strategies are scaled across the enterprise, and AI is introduced into operations.
- **Leap 4 (Adaptive Practices):** Business and clinical activities actively adapt to evolving situations, with AI supporting complex decision-making and autonomous technology pilots emerging.
- **Leap 5 (Supervised Automation):** Full realisation of a smart hospital, with interconnected systems, embedded AI for adaptive clinical and operational decision support and fully digitised patient experiences.

This structured approach helps institutions understand their current state and chart a path toward greater smart technology-assisted clinical and administrative operations.

As of early 2025, over 180 US hospitals have completed the survey. Early findings show larger hospitals (over 250 beds) have progressed farther on the smart hospital scale than smaller institutions. Scores are higher in the domain of Humans compared to Environments and Processes, reflecting a strong focus on electronic communications between patients and clinicians. Significant engagement of clinical staff in smart care strategy, selection and adoption is evident.

Key Trends and Insights from SHMM Survey Findings

There is a strong and growing focus on enhancing smart processes across healthcare organisations, particularly in for-profit systems where efficiencies and savings serve as key drivers of innovation. Respondents from the SHMM survey highlight the prioritisation of technologies aimed at addressing critical workforce challenges, including clinician burnout, job satisfaction and enabling flexible or alternative work arrangements. In response to these needs, ambient technologies—such as patient listening systems, real-time monitoring and voice-activated solutions—are seeing increased adoption. These innovations also support virtual nursing models, which can alleviate pressure on in-person clinical staff while maintaining high standards of patient care.

Another notable trend is the movement away from isolated point solutions toward integrated technology platforms that provide seamless, enterprise-wide functionality. While descriptive and diagnostic analytics remain the most commonly deployed forms of data analysis across healthcare settings, there is a clear

emergence of predictive and prescriptive analytics, suggesting a maturing analytical capacity within the sector. AI implementation plans are widespread, with decision support systems being the most common application in clinical environments. Importantly, the SHMM recognises that digital transformation is not a strictly linear journey; healthcare organisations often advance in some domains while lagging in others, underscoring the complexity and multifaceted nature of becoming a truly "smart" hospital.

Transforming Healthcare Revenue Cycles with AI: A Strategic Role for SHMM

Healthcare revenue cycle management (RCM) is essential to the financial stability of healthcare systems. Covering the patient journey from appointment scheduling to final claim settlement, RCM involves processes where inefficiencies can lead to denials, delayed payments and financial strain.

Traditionally reliant on manual workflows, revenue cycle operations are now being transformed through artificial intelligence (AI). AI introduces automation that reduces errors and enhances efficiency, particularly in missed charge capture, predictive analytics for denial likelihood and real-time integrity audits. According to Smart Hospital Maturity Model (SHMM) survey findings, 45.5% of leading healthcare organisations already use AI to validate claims, moving beyond theory into practice.

Key AI applications in RCM include scanning patient records for missing charges, predicting claim denial risks and conducting real-time claim audits. These improvements reduce denials, accelerate payments and lower administrative burdens, ultimately improving patient experience and financial performance.

However, challenges such as data quality, regulatory compliance, workforce readiness and upfront costs remain. Here, the SHMM offers crucial strategic guidance, helping institutions assess digital capabilities, set goals, adopt AI incrementally and foster interdisciplinary collaboration.

Through the SHMM's structured framework, healthcare providers can confidently implement AI solutions, ensuring sustainable improvements in revenue cycle operations and supporting broader digital transformation. As AI's role expands into payment posting, appeals management and predictive modelling, the SHMM ensures hospitals evolve alongside the demands of a smart healthcare ecosystem.

Meeting the Growing Demand for Healthcare Data Storage

Healthcare organisations today manage massive volumes of data from EHRs, imaging files, real-time patient monitoring and telemedicine data. While 73% of HCOs believe they can adequately address inpatient data demands today, confidence drops significantly when projecting five years ahead, especially in residential care settings.

The rapid growth of healthcare data is driven by the digitisation of patient records, advances in medical imaging, remote monitoring, telehealth, precision medicine and increased use of AI and analytics. Each trend contributes significantly to the storage burden.

> "The vision of a fully integrated, intelligent healthcare system is within reach for those willing to embrace the smart hospital journey."

Inpatient care remains the most data-intensive setting, with ambulatory settings also generating large volumes of data. Residential care, driven by remote monitoring and wearable devices, is emerging as a major source of new data. However, only 36% of HCOs currently feel well-prepared for residential data demands.

Current infrastructure may fall short in five years due to ageing legacy systems, siloed data and interoperability gaps, regulatory pressures and data retention requirements, rise of edge and IoT devices and security and disaster recovery considerations.

The SHMM framework guides institutions in assessing current capacities, planning strategic upgrades, implementing phased improvements and maintaining continuous improvement cycles. Because data storage underpins advanced analytics, AI and transformative technologies, storage infrastructure improvements are critical.

Strategies for upgrading storage infrastructure include hybrid cloud adoption, data tiering and lifecycle management, edge computing for residential care, interoperability initiatives, enhanced security and encryption and AI and machine learning for proactive storage management.

Advancing Through the Analytics Maturity Curve

Advanced analytics is central to healthcare digital transformation. Healthcare analytics progresses from descriptive to diagnostic, predictive, prescriptive and generative analytics. Descriptive analytics summarise historical data; diagnostic analytics explore root causes. Predictive analytics forecast future outcomes; prescriptive analytics suggest optimal interventions. Generative analytics creates new content, suggestions, or solutions based on learned patterns.

While descriptive and diagnostic analytics are widely adopted (100% and 91%), predictive analytics usage drops to around 32% for clinical decisions, prescriptive analytics are used by less than half of the surveyed hospitals, and generative analytics adoption remains very low.

Barriers to advanced analytics adoption include data quality and silos, regulatory and compliance concerns, lack of skilled workforce, clinician trust and buy-in and financial constraints. The SHMM helps organisations set realistic goals, ensuring alignment between strategic objectives and analytics ambitions.

Unlocking the Future Potential with Advanced Analytics

Moving from descriptive to generative analytics requires incremental steps: starting with high-ROI projects, focusing on data governance, fostering multidisciplinary collaboration, ensuring ethical and regulatory readiness and continuing education and training.

Starting small with high-impact projects can quickly demonstrate value and drive enthusiasm. Investing in data governance improves model accuracy. Multidisciplinary collaboration builds trust and ensures relevance. Ethical and regulatory readiness maintains patient trust, and ongoing training cultivates a culture of data-driven decision-making.

As healthcare organisations climb the SHMM ladder, they gain greater confidence in using advanced analytics. Confidence eventually extends to clinical care, enabling providers to personalise treatments, streamline diagnostics and reduce human error. Unlocking the full potential of data transformation is critical for healthcare providers to position themselves as truly ‘smart’ hospitals.

Conclusion: Toward a Smart, Integrated Healthcare Future

The Smart Hospital Maturity Model offers healthcare leaders a comprehensive blueprint for navigating smart aspects of digital transformation. From implementing smart technologies and AI-driven RCM solutions to upgrading data storage and advancing through analytics maturity, the SHMM emphasises steady, strategic progress.

Healthcare’s shift toward connected care spanning inpatient, ambulatory and residential settings brings tremendous benefits but also substantial demands for robust data storage solutions. Although many organisations currently meet their immediate storage needs, the next five years promise a steep escalation in data volume.

By leveraging the SHMM framework, healthcare organisations can systematically assess readiness, implement strategic upgrades and confidently approach emerging data challenges. Combined with best practices like hybrid cloud adoption, interoperability standards and strong security protocols, healthcare providers can securely store, manage and use data at scale.

Proactively addressing challenges related to data quality, compliance, workforce readiness and financial investment unlocks the full potential of AI and advanced analytics. Doing so not only improves financial performance and reduces administrative burden, but also enhances the overall patient experience by ensuring timely, accurate and transparent billing.

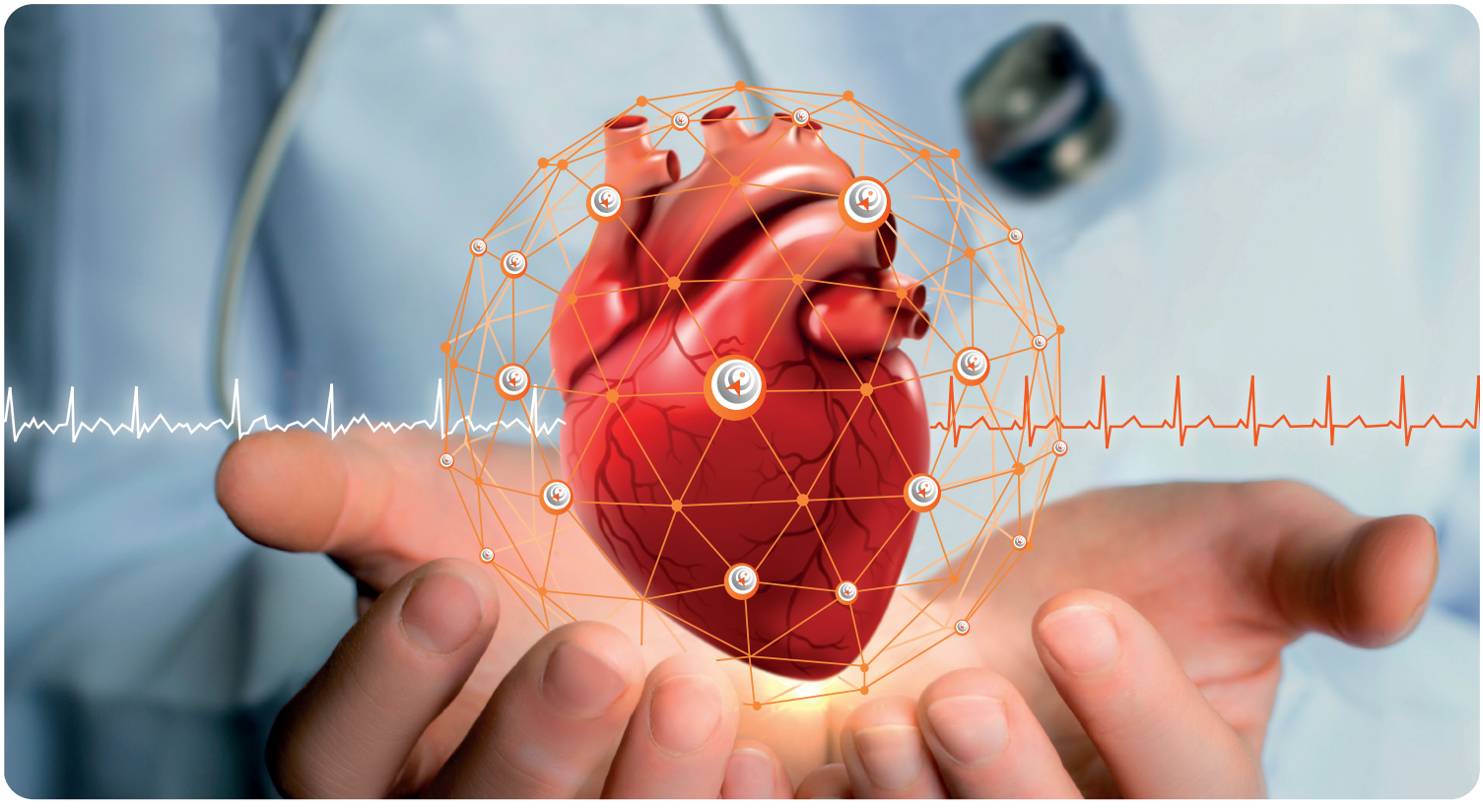
Ultimately, through careful planning, trust-building and collaboration, healthcare providers can harness the full potential of data and technology to transform care delivery, ensuring operational excellence and patient-centred care in the years to come. The vision of a fully integrated, intelligent healthcare system is within reach for those willing to embrace the smart hospital journey.

Conflict of Interest

None

Rapibloc®
Landiolol hydrochloride

Rapid Rate Control with Myocardial Protection[1]



Rapid control of ventricular rate in patients with SVTs and AF[1]

First-line for patients with cardiac dysfunction[2]

- **Limited effect** on blood pressure and inotropy[3]
- **Favourable safety profile for patients with renal and hepatic comorbidities** due to inactive metabolites and hydrolysis by plasma esterases[1,4]
- **Compatible with pulmonary disorder patients** due to highest cardioselectivity (β1/β2-selectivity = 255:1) among β1-blockers[5]
- **Limited rebound and tolerance effect** due to lack of pharmacochaperoning activity[6]

Rapibloc® 300 mg: Rapibloc® 300 mg powder for solution for infusion. **Composition:** A vial of 50 mL contains 300 mg landiolol hydrochloride which is equivalent to 280 mg landiolol. After reconstitution each mL contains 6 mg landiolol hydrochloride (6 mg/mL). Excipients with known effect: Mannitol E421, sodium hydroxide (for pH adjustment). **Therapeutic Indication:** Landiolol hydrochloride is indicated for supraventricular tachycardia and for the rapid control of ventricular rate in patients with atrial fibrillation or atrial flutter in perioperative, postoperative, or other circumstances where short-term control of the ventricular rate with a short acting agent is desirable. Landiolol hydrochloride is also indicated for non-compensatory sinus tachycardia where, in the physician's judgment the rapid heart rate requires specific intervention. Landiolol is not intended for use in chronic settings. **Contraindications:** Hypersensitivity to the active substance or to any of the excipients, severe bradycardia (less than 50 beats per minute), sick sinus syndrome, severe atrioventricular (AV) nodal conductance disorders (without pacemaker): 2nd or 3rd degree AV block, cardiogenic shock, severe hypotension, decompensated heart failure when considered not related to the arrhythmia, pulmonary hypertension, non-treated phaeochromocytoma, acute asthmatic attack, severe, uncorrectable metabolic acidosis. For further information on warnings and precautions for use, interaction with other medicinal products and other forms of interaction, fertility, pregnancy, lactation, effects on ability to drive and use machines, unsiderable effects, and habituation effects, please refer to the published SmPC
Prescription only/available only from pharmacy. Date of revision of the text: 02/2024. **Marketing authorization holder:** Amomed Pharma GmbH, Leopold-Ungar-Platz 2, 1190 Vienna, Austria

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Closed-Loop Medication Logistics: Enhancing Patient Safety and Reducing Work Burden for Medical Staff by Smart Cabinets

Smart cabinets support closed-loop medication logistics by reducing errors, enhancing patient safety and lowering staff workload. Despite proven benefits, adoption in German hospitals remains low due to lack of awareness, change resistance and staffing constraints. Studies show smart cabinets cut costs, improve efficiency and gain nurse approval, especially in high-pressure settings like ICUs. Integration with clinical pharmacists further boosts medication safety.

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key points

- Smart cabinets reduce medication errors and improve patient safety in hospitals.
- Nurses report lower workload and more time for patient care with automated systems.
- Closed-loop systems ensure accurate drug delivery using digital tracking technologies.
- German hospitals show resistance due to limited awareness and digital transformation fears.
- Smart cabinets offer cost savings by reducing waste, errors and hospital stay lengths.

Introduction

Reducing healthcare costs has become a crucial concern for hospitals as well as for health policymakers and payers. Pharmaceuticals are recognised as an important cost driver in all developed healthcare systems. In Germany, expenditure on drug-related therapies amounted to €55.2 billion in 2024 (VDEK 2025).

A second major cost driver for hospitals is preventable adverse drug events. In German hospitals, between 19% and 35% of all incidents causing harm to patients are attributable to medication errors, leading to an estimated 15,000 patient deaths (von Eiff W 2021a). Furthermore, about 14% of the average length of stay in German hospitals is attributable to unplanned drug interactions, and 6.5% of all admissions to emergency departments are caused by adverse drug reactions (Schurig et al. 2018).

About 4.5% of acute care patients are victims of an adverse drug event (ADE) (Stausberg et al. 2011). Between 30% and 55% of these ADEs are considered as avoidable (von Eiff W 2021a). When admitted to hospital, 34% of patients suffer from side effects related to their drug therapy, of which only 29% were classified as “inevitable”, so that the remaining 71% are the consequence of medication errors (von Eiff W 2021a). Several studies have shown that drug-related hospitalisations account for between 2.4% and 6.2% of all medical admissions (Schneeweiss et al. 2002; Pirmohamed et al. 2004; Just et al. 2020).

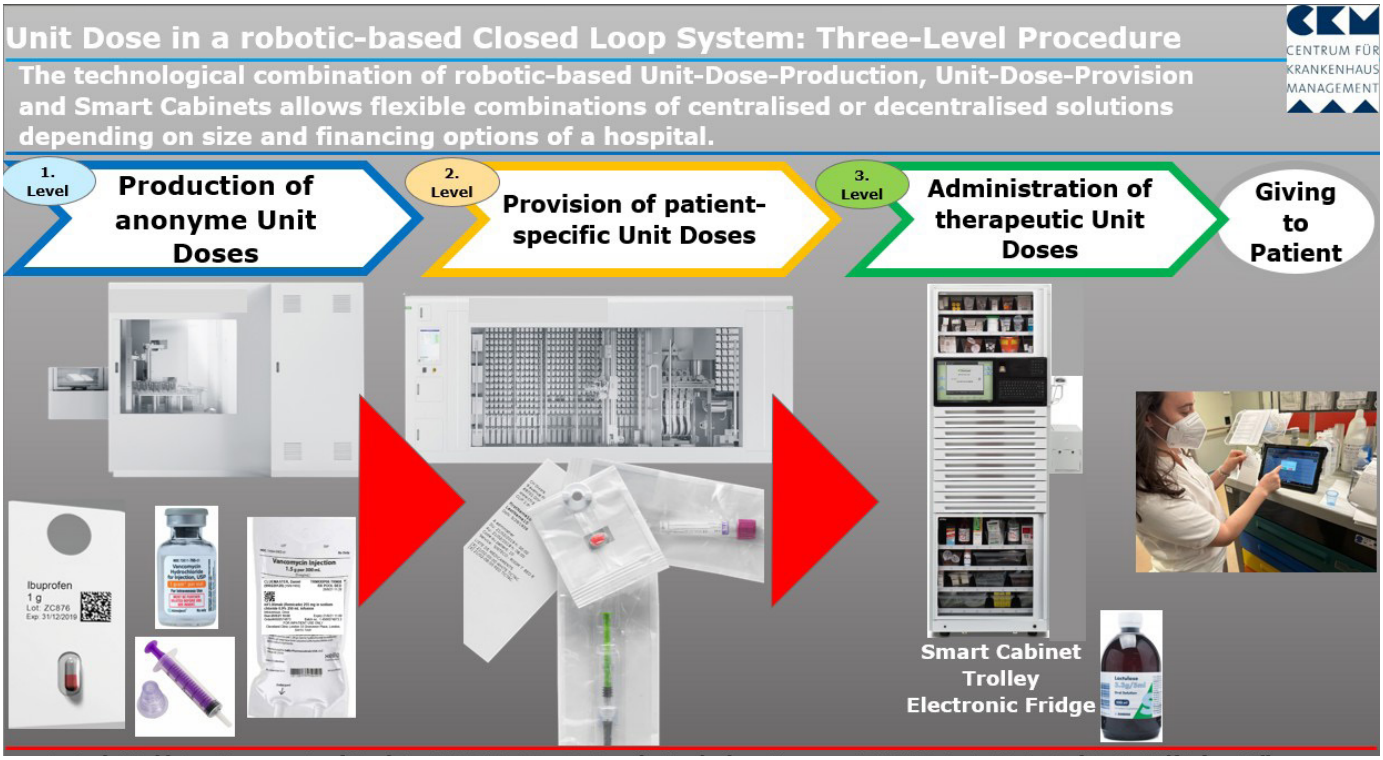

Figure 1: The concept of closed-loop medication administration aims to provide a patient-specific therapeutic unit dose through a three-level production process, without any manual handovers or media gaps (Source: Own representation based on own research).

The consequences for patients range from nausea and vomiting to temporary health impairment, the need for additional therapies and prolonged hospital stay, along with an increasing risk of nosocomial infection. In the worst case, the patient may experience sustainable health impairments or die.

in Germany is estimated to range between €800 million and €1.2 billion (Sommer et al. 2018).

Complexity Causing Errors

In Germany, more than 104,000 different drugs are approved, of which 56,000 are prescription medications.

> "Almost all respondents (95%) reported having encountered an ADE during their career, and 90% of this cohort attributed these events to human error."

Regardless of the risks to patients, every non-fatal medication error leads to an average of €3,000 and €4,000 in additional costs. The length of stay (LOS) may be extended between 1.7 and 8.5 days per case. This leads to opportunity costs due to lost contribution margins ranging between €7,000 and €15,000, depending on the type of interventions (eg total knee arthroplasty, coronary artery bypass graft, transfemoral valve intervention) (von Eiff MC et al. 2019). The total annual cost of treatment caused by medication failures

Furthermore, 3,000 active ingredients and more than 6,600 known ingredient interactions make medication therapy a highly complicated and risky decision-making process (BMG 2021).

Also, the entire medication process, from drug anamnesis at admission to the decision on drug therapy at discharge, is a complex and highly collaborative workflow with many risks of failure. These include prescription errors by physicians, improper storage, inadequate monitoring of drug expiration dates,

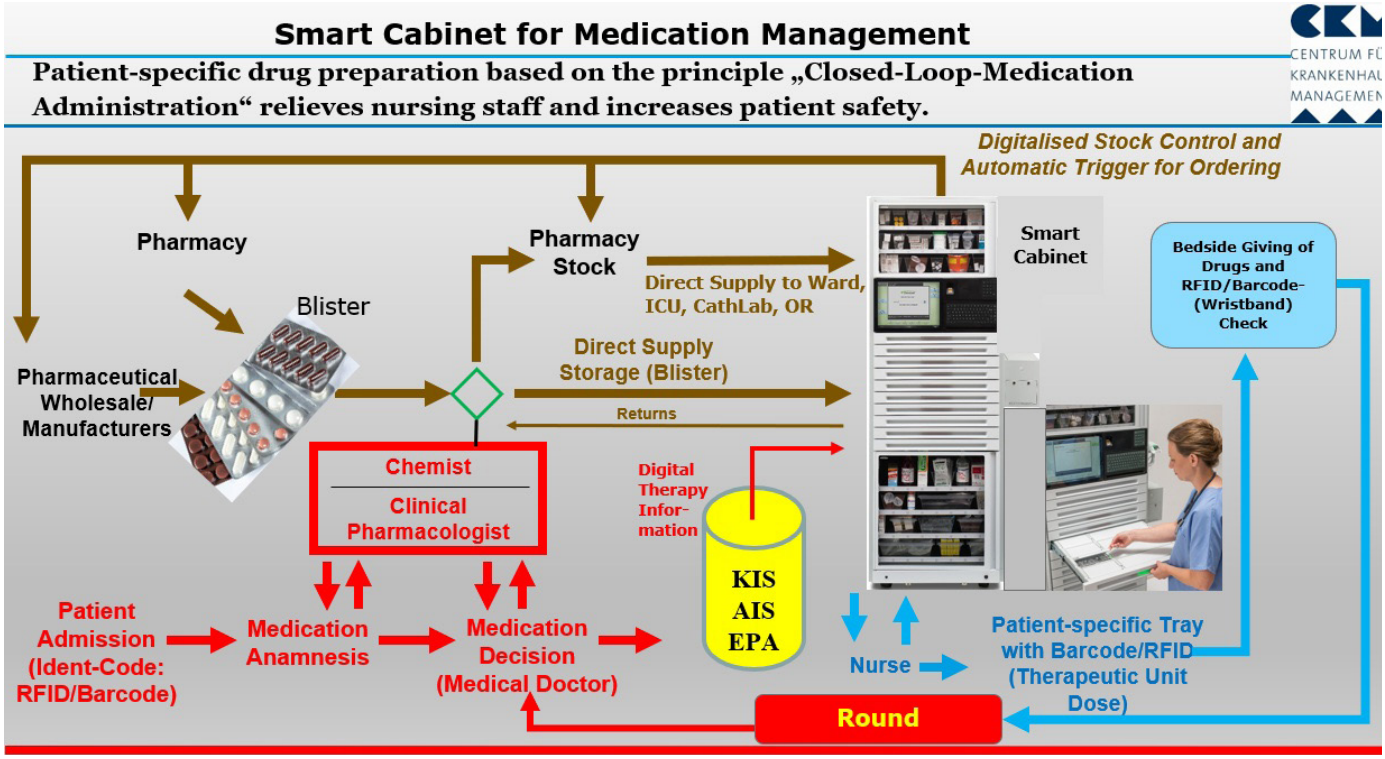

Figure 2: Generic process map for closed-loop medication administration, combining unit dose delivery with a smart cabinet as the digital backbone (Source: Own representation based on own research).

drug confusion, look-alike and sound-alike errors, inappropriate drug composition for individual patients and failures in drug administration. An important contributing factor to these failures is the increasing work burden for physicians and nurses, accompanied by time pressure and, as a consequence, a growing stress level.

Poor Organisation Leading to Failures

In most German hospitals, the medication management system is far from closed-loop safety requirements (von Eiff W 2021b):

- In 61% of hospitals, the pharmacy delivers the necessary drugs in bulk to the ward stock. From this stock, nurses allocate medication according to patient needs and physician prescriptions.
- In 57% of the hospitals, the matching between patient and medication is performed by nurses through visual checks.

Based on experience, both of these workflows are extremely prone to error.

Work Burden for Nurses: A Reason for Medical Errors

Nurses, who typically suffer from work overload, are particularly exposed to the risks of error-prone medication logistics. Between 26% and 44% of all failures occurring in the medication administration process emerge through activities in which nurses are substantially involved (Brinkrolf et al. 2013).

Nursing workload has increased significantly due to a gradual economisation of healthcare. In German hospitals alone, accumulated nursing overtime is equivalent to 17,800 full-time positions (von Eiff MC et al. 2022).

During the coronavirus crisis, working conditions deteriorated dramatically, especially for nurses caring for ventilated patients on the intensive care unit (ICU). Additional overtime, high patient mortality, resource-intensive and stressful care requirements have led to prostration and mental exhaustion.

As a result of this tremendous burden on nurses and physicians during the pandemic, up to 30% of these professionals reported inadequate working conditions and expressed their intention to quit their jobs. The focus of the complaints was the lack of digitalised equipment that could contribute to a safer and more resilient working environment.

In order to identify further reasons for unsafe drug administration, 80 nurses working in different German hospitals on various types of wards were surveyed by the authors. Their experiences with adverse drug events,

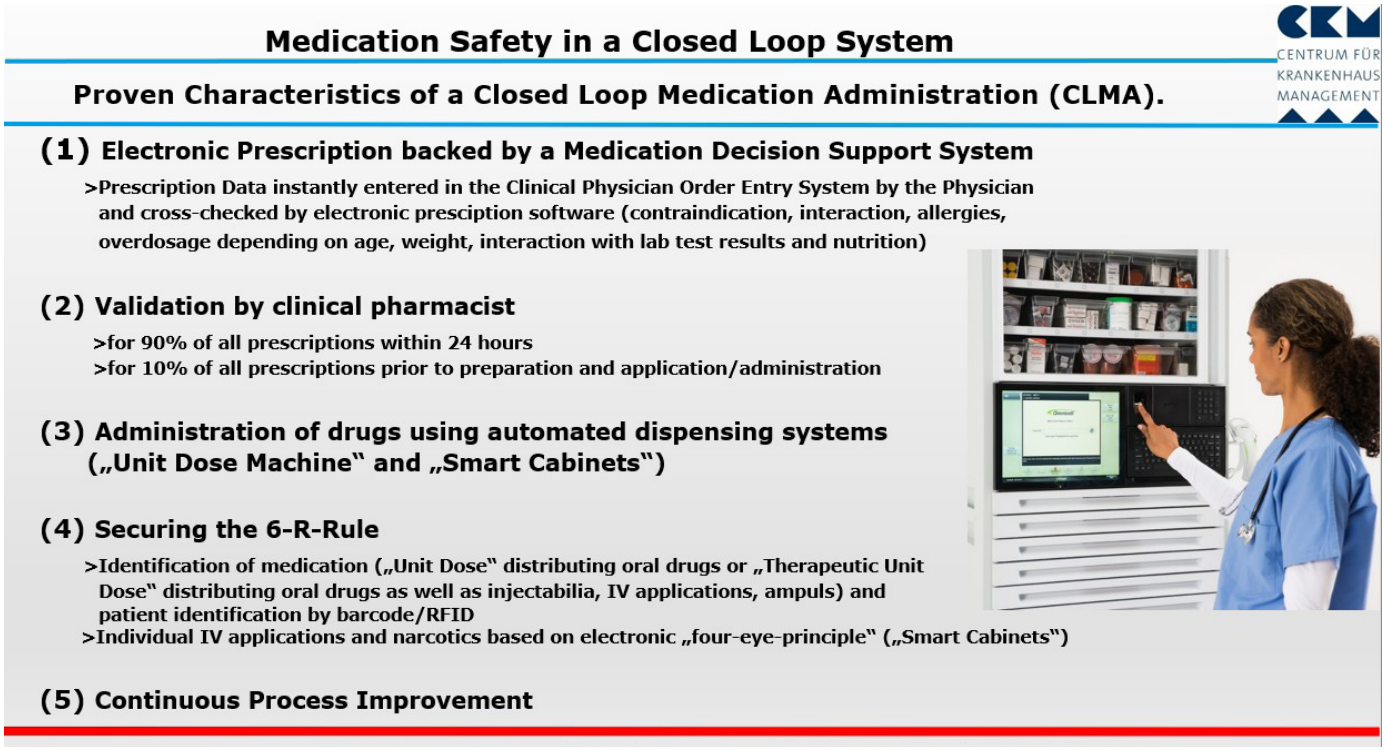

Figure 3: Necessary preconditions a closed-loop system must fulfil in practice (Source: Own representation based on own research).

as well as their knowledge of closed-loop concepts and the functionality of automatic drug dispensing systems (NURSE-DRUG Study; based on own research) were evaluated. The results were astonishing:

- Almost all respondents (95%) reported having encountered an ADE during their career, and 90% of this cohort attributed these events to human error.
- 19% stated that drug administration failures occurred every working day, and further 36% indicated such incidents happen at least once a week.
- Some 50% identified persistent staff shortage to be the most important cause of errors.
- 75% declared to have witnessed a case where a wrong patient received medication despite the preparation being patient-specific and correctly prepared.
- 65% characterised the process of ordering pharmaceuticals via hospital pharmacy as time-consuming.
- Some 46% of the nurses were unfamiliar about unit dose technologies and closed-loop concepts, while another 30% reported to have only limited knowledge about the functioning and workflow impacts of smart cabinets.

In summary, it seems necessary to familiarise nursing staff with drug dispensing technologies and their potential to simplify medication workflows, and to improve safety by reducing the risk of error.

> "Smart cabinets contribute significantly to reducing adverse drug events."

A Need for Establishing Safety Standards in Legal Regulation of Medication Management

In order to overcome typical failure modes, the German government decided in 2020 to legally require hospitals to organise their medication management to be as error-free as possible (von Eiff W et al. 2023). A closed-loop administration system in combination with a unit dose

approach was designated as the “gold standard” in medication management.

A closed-loop system is a feedback-controlled, robust and failure-tolerant self-steering system. Barcodes or RFID transponders are used to identify patient medications, ensuring the correct match between the patient and the medication.

To put the closed-loop process in order, electronic verification should be used to confirm “the six rights”: the right patient, the right medication, the right dose, the right time, the right dosage form and the right documentation, based on digital recording technology at the bedside. All of these elements must align to ensure safe and accurate medication administration.

provision and administration, and patient intake at the bedside (see Figure 1).

In order to ensure proper medication treatment under these conditions, smart cabinets (SC) are used as a backbone in a digitalised medication chain. The “final product” of a closed-loop system is the **therapeutic unit dose,** an RFID-tagged tray containing the complete medication arrangement (oral drugs, injectables, ointments etc.) to be administered to a specific patient at a defined date.

The different types of medication are retrieved from the smart cabinet by a nurse. This selection and withdrawal process is controlled by so-called guided lights, which ensure that only the shelves containing medication

> “Not a single respondent (0%) reported having a clear understanding of how smart cabinets function.”

Closed-loop medication requires the entire medication administration chain to be electronic, with no point at which data is transferred via printed materials. All medication data must be accessible in real time to all professionals involved in the patient´s treatment process. This continuous electronic availability eliminates information gaps and significantly reduces the potential for errors.

Basically, unit dose attribution to the patient applies to orally administered drugs. Therefore, in every medication logistics system organised according to the “Closed-loop Medication Administration” principle, the challenge lies in addressing the following issues:

- How to manage the administration and flow of prepared or ready-to-use syringes, injectables, ampules and therapeutic ointments?
- How can drugs that need to be stored in a fridge be integrated into the workflow?
- How to administer and organise the flow of medications brought in by the patient?
- How is the therapeutic unit dose assembled and allocated to the patient? Is the “last mile”, from the nurse’s preparation of the patient-specific therapeutic unit dose to its observed intake, organised in a “poka-yoke” (fail-safe) way?

To answer these questions, it is helpful to distinguish between three levels of medication process: production,

assigned to the specific patient can be opened. Combined with medication test software, this helps to prevent allergic reactions and incorrect medication intake.

From a logistical point of view, each medication withdrawal from the smart cabinet initiates an end-to-end routine checking minimum stock levels, triggering stock replenishment and billing processes automatically without requiring human intervention.

The Generic Process Map and the Role of Smart Cabinets

In order to establish an integrated medication administration process that meets all requirements for safe, efficient and effective drug delivery, including all medication types and administration forms, a Generic Process Map was developed (see Figure 2).

The generic process map explains the interdependencies between the processes of medication logistics and medication administration. It also demonstrates the pivotal role of a smart cabinet as an integrative element that controls the entire medication management system, oriented towards patient safety, economic efficiency and medical effectiveness. This process design is based on the Pull Principle, where patient needs act as the driving force behind demand—a concept well known from lean management (Liker 2004).

Implementing a closed-loop system in practice requires the fulfilment of well-defined criteria and proven functional characteristics (see Figure 3).

From the perspective of the German healthcare system, the most important precondition for establishing safe and effective medication management is the presence of a clinical pharmacist on the ward as a consulting resource for the physician. However, this basic requirement cannot be fulfilled because of a significant shortage of pharmacists. While in U.S. hospitals six pharmacists are assigned per 100 beds, and NHS hospitals in the UK maintain a ratio of a 4:100, German hospitals operate at just 3 pharmacists per 1000 beds (0,3:100 ratio) (AKWL 2024).

There is evidence that the number of clinical pharmacists working in close cooperation with clinicians directly affects the incidence of adverse drug events (Bond 2006). Currently, fewer than 50% of German hospitals employ clinical pharmacists on the ward to support a safer, patient-centred medication administration process (von Eiff MC et al. 2022).

Results

By analysing findings from the literature, the effects of smart cabinets (also referred to as electronic medication cabinets, EMC, or automated dispensing cabinets, ADC), used as the backbone of the medication administration process, have been identified. Several case studies show that electronic cabinets contribute significantly to improved patient safety in drug therapy and help prevent drug-related opportunity costs caused by extended hospital stays, worsened outcomes and the need for additional therapies, all in once.

The results are categorised into four areas of evaluation criteria:

Employee Acceptance and Satisfaction with Smart Cabinets

Smart cabinets (SC) significantly relieve nursing staff of all logistical tasks. This effect is an important reason for the acceptance of this new innovative technology that has the potential to reorganise workflows and to change the way different professional groups cooperate. Furthermore, from the engineering sciences, we know that employee acceptance is a major precondition for the efficient and effective technology use in day-to-day work processes (von Eiff MC et al. 2019).

Most nurses favour the implementation of an automated dispensing system because of a marked reduction in medication errors related to drug picking, preparation and administration, especially in intensive care units (Craswell et al. 2021; Chapuis et al. 2022). Nurses also report spending less time on medication-related activities, with one study indicating an average of 14.7 hours saved per day on a 33-bed ward (Chapuis et al. 2015).

In another study, 80% of nurses in an ICU and 42% in an operating room found SCs to make their work easier. On average, time spent on dispensing and preparing medications was reduced on by 32 minutes per 8-hour shift, so that more time could be spent on direct patient care activities (Metsämuuronen et al. 2020).

Contribution to Patient Safety

A before-and-after comparison between two intensive care units in a 2,000-bed university hospital showed that, following the implementation of an automatic dispensing system on one ICU ward, the percentage of total opportunities for error was reduced significantly from 20.4% to 13.5% (Chapuis et al. 2010).

> “Smart cabinets significantly relieve nursing staff of all logistical tasks.”

A deeper analysis showed a significant impact of SCs on preparation errors reduction. Medication errors related to drug picking and administration were also reduced. Overall, a decline in medical errors from 3.5 to 0.5 per 1,000 patients can be achieved (von Eiff W 2021a).

Efficiency, Cost Containment Effects and Return on Investment

Smart cabinets contribute significantly to reducing adverse drug events, helping to avoid opportunity costs caused by an extended length of stay—on average, 2.9 additional days (Rottenkolber et al. 2012). The additional costs of a patient suffering from an adverse drug event are tremendous and not reimbursed by the sickness funds (medical aid funds).

Direct treatment costs for such patients range between €1,500 and €2,700 per case. In addition, opportunity

costs have to be mentioned: a 2.9-days stay extension means that 2 to 3 ADE patients cause a loss of revenue for at least one surgical procedure, such as total hip replacement, total knee arthroscopy or transapical valve intervention, which typically involves a 6- to 9-day length of stay. This results in a loss of contribution margins estimated between €7,500 and €20,000 (von Eiff MC et al. 2019).

Furthermore, SCs reduce drug storage costs, mainly by preventing expiration (Bourcier et al. 2016). A comparison of drug stock and consumption across various internal medicine wards over a one-year period showed a reduction of 61% when an SC was in operation (Bourcier et al. 2016; Monzón Moreno et al. 2016). The same sources report that the costs of implementing one SC (€61,000 over five years) can be recouped in 4.4 years.

Bonnabry & Francois (2020) report annual savings of 0.2 full-time equivalents (€21,000) per smart cabinet located in a 33-bed ward. Moreover, drug usage was reduced by 5% of the total medication budget, and a further 1% of the budget could be saved by avoiding shortages. Compared with traditional warehousing management approaches such as the KANBAN principle ("split supply") (Kenney 2011) or the use of supply chain assistants, SC technology leads to 30% lower storage and inventory costs.

Finally, using electronic cabinets to provide the wards with controlled substances contributed to substantial time savings. For an average 24-patient ward, time spent on ordering and inventory activities was reduced by 80 to 120 minutes per day (von Eiff W 2020).

Evuation of SCs from the Viewpoint of Hospital Managers and Pharmaceutical Decision-Makers

Despite these convincing results reported by different hospitals from various countries, German hospital managers (including CEOs, procurement officers and pharmacists) have not so far been willing to implement smart cabinets in their institutions. Therefore, no smart cabinet-based medication processes are currently in place in German hospitals.

In order to determine the reasons behind this persistent refusal to adopt electronic cabinets, despite their successful implementation in hospitals outside Germany, 59 decision-makers of German hospitals were surveyed (von Eiff W 2020). The findings revealed several surprising insights:

- 56% of the decision-makers in German hospitals stated they refused to consider the potential of cabinet solutions due to being satisfied with their current systems.
- This attitude stands in conflict with the fact that in 57% of German hospitals, the matching of patient and medication is operated via sight control by the nurse, without any digital support. Furthermore, only 33% of hospitals use medication testing software to enable early detection of drug interactions.
- 84% of the decision-makers criticised a lack of reliable cost-benefit analyses for the SC system, despite the availability of studies demonstrating the benefits of smart cabinets for patient safety and staff workload reduction.

> "A decline in medical errors from 3.5 to 0.5 per 1,000 patients can be achieved."

- Not a single respondent (0%) reported having a clear understanding of how smart cabinets function or being adequately informed about the various smart cabinet solutions available on the market.
- Interestingly, a significant number expressed fear of not being able to manage the transition from traditional medication logistics to a digitally based system using smart cabinets.

Discussion

The generic process blueprint, combined with best-in-class reports, was expected to convince decision-makers of the positive effects of electronic cabinets—namely, increased patient safety, reduced nursing workload and higher cost-effectiveness.

However, experience shows that innovative technologies bring changes to workflow organisation and disrupt established interprofessional routines. As a result, many employees fear being unable to fulfil the requirements of the new work environment and anticipate being overburdened by additional tasks and responsibilities.

Keeping this in mind, the successful implementation of electronic cabinets requires several elements:

- an effective change management organisation in order to support employees during the implementation process,
- a convincing and reliable cost-benefit analysis,
- a detailed description of the reorganised workflow based on smart cabinets and
- a summary of the advantages employees can expect for themselves from the new workflow.

Thus, an effective change management organisation can be recognised as a dominant success factor when implementing an ADC-based closed-loop medication administration system (Hänninen et al. 2021).

From the field of workplace engineering, it is established that work efficiency, measured in terms of therapy effectiveness, economic performance and patient safety, is mainly determined by staff acceptance of new technologies and reengineered workflows (von Eiff MC et al. 2019).

Significant investments—especially those with substantial effects on working behaviour, interprofessional cooperation and changes in workflows, responsibilities and tasks—often encounter financial barriers. The demonstration of a positive return on investment (ROI) is often necessary to secure board-level approval.

SC technology seems to be most effective and efficient in intensive care units, emergency departments, internal medicine wards, operating theatres and oncological departments—settings known for the rapidity of changes in medication schemes.

Moreover, SCs are ideally suited to support the realisation of a closed-loop medication administration system that includes all dosage forms. They address a key limitation of traditional unit dose systems, which focus almost exclusively on oral medications.

Against this background, it becomes evident why SC technology also plays a major role in the leadership concept of Magnet Nursing (von Eiff AKS et al. 2020). The Magnet Nursing model implies a cause-and-effect correlation between working conditions and nurse staffing on one hand, and defined outcome indicators on the other. In Magnet hospitals, SCs help avoid medication errors by reducing work pressure and lowering stress levels of nursing staff.

Last but not least, it is essential to consider that the efficiency and effectiveness of SC-based medication logistics depend on the precision and quality of drug therapy. Studies show that medication decisions can be significantly improved by involving clinical pharmacists in a collaborative approach with physicians and nurses. For instance, interventions by clinical pharmacists have contributed to reducing polypharmacy rates from 42.2% to 12.2% (Ságiné et al. 2022). In another study reviewing 1,329 prescriptions, 9.6% of prescription errors, 9.8% of dispensing and administrative errors, and 9.9% of dosage errors were identified (Berger et al. 2022). Hence, SCs and clinical pharmacists are important success factors when establishing a fail-safe medication management environment.

It must also be acknowledged that digitalised work processes are increasingly vulnerable to cyberattacks and IT failures. Therefore, when implementing SC technology, it is recommended to integrate SCs in a cyber-secure and fail-proof IT environment.

Conflict of Interest

None

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Advancement of 3D Printing in Healthcare and Its Impact on Sustainability

3D printing is transforming healthcare through personalised devices, surgical precision and faster prototyping while advancing sustainability. On-demand production reduces waste, supports circular economy models and lowers carbon footprints by minimising transport and inventory. Despite its promise, challenges remain, including regulatory gaps, cost barriers, material limits, cybersecurity risks and skill shortages. Overcoming these hurdles could unlock more efficient, sustainable and accessible care.

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key points

- 3D printing enables personalised medical devices and surgical precision.
- On-demand production reduces waste and lowers carbon emissions.
- Circular economy models recycle hospital plastic into printing materials.
- High costs, material limits and regulatory gaps hinder wider adoption.
- Skill shortages and cybersecurity risks remain key implementation barriers.

The healthcare sector is undergoing a profound transformation, partially driven by the rapid advancements in 3D printing, also known as Additive Manufacturing (AM). This article provides an examination of the current state of 3D printing in healthcare, detailing its diverse applications, the paradigm shift introduced by Design for Additive Manufacturing and the technology's profound impact on fostering sustainable healthcare practices, particularly through waste reduction, circular economy principles and the provision of precision medical devices.

The article also addresses the significant challenges hindering widespread adoption, including regulatory complexities, intellectual property concerns, cybersecurity risks, material limitations, cost barriers and the critical skill gap. Ultimately, it is offering a forward-looking perspective on how to overcome these impediments, accelerate the integration of 3D printing and fully unleash its potential to create a more personalised, efficient and environmentally responsible healthcare future.

Introduction: Reshaping Healthcare with Additive Manufacturing

The modern healthcare landscape is experiencing a profound revolution, propelled by the groundbreaking advancements in 3D printing technology. Unlike traditional subtractive manufacturing methods that remove material from a larger block, AM constructs three-dimensional objects layer by layer from digital models, offering unprecedented design freedom and material efficiency (Greenwood 2024). This fundamental difference has positioned 3D printing as a paradigm-shifting technology with the capacity to redefine patient care, surgical techniques and the development of medical devices and pharmaceutics.

The Current Landscape of 3D Printing in Healthcare

Where We Are Today: A Snapshot of Advancements

The medical 3D printing market is experiencing unprecedented and rapid expansion. Projections indicate a robust growth from $2 billion (€1.8 billion) in 2022 to $4 billion (€3.6 billion) by 2026, representing a 21% Compound Annual Growth Rate (CAGR) (Jaycon 2025). The broader 3D printed medical device market is anticipated to reach an impressive $16.5 billion (€14.9 billion) in revenues by 2034 (Saunders 2025). The dental 3D printing market alone has demonstrated significant maturity and growth, surpassing $3 billion (€2.7 billion) in 2023 and continuing to expand at over 20% annually (Jaycon 2025). The increasing trend of healthcare providers establishing in-house 3D printing facilities further underscores this rapid adoption, with the number of hospitals maintaining such capabilities growing significantly from just three in 2010 to 113 in 2019 (AHA n. d.).

> “The integration of 3D printing (…) represents a fundamental shift toward more personalised, efficient and accessible medical care.”

The historical trajectory of 3D printing in medicine traces back to the 1980s. Early, significant medical applications emerged with the 3D-printed synthetic human bladder in 1999, followed by the landmark FDA approval of the first 3D-printed drug, Spritam, in 2015 (Greenwood 2024). These pioneering achievements underscored the technology’s immense potential to disrupt healthcare industry.

The integration of 3D printing into healthcare represents a fundamental shift toward more personalised, efficient and accessible medical care. This transformation is particularly vital in addressing pressing challenges in modern healthcare, such as the escalating demand for highly customised medical solutions, increasing cost pressures on healthcare systems and the urgent global need for more sustainable practices, all of them part of the strategic actions towards sustainability (Avanija 2025). Sustainable healthcare, defined as a holistic approach which encompasses products, services and healthcare operations with superior environmental performance, without compromising with the quality level of the care itself, balancing current and future health needs with environmental limits to ensure a healthier planet for future generations, finds a pivotal ally in 3D printing.

Key applications are transforming patient care across various medical specialties. In Implants and Prosthetics, patient-specific implants, particularly in orthopaedics and dentistry, were among the earliest and most impactful medically approved uses of 3D technology (Cong et al. 2025). Anatomical Models and Surgical Guides represent another critical application. 3D printers can produce highly accurate and detailed anatomical models, invaluable for assisting surgeons in preparing for complex procedures. This leads to increased surgical precision, reduced operative times (eg a mean reduction of 62 minutes, resulting in a cost savings of $3,720 (€3,350) per case) and improved patient outcomes (AHA n. d.). In Pharmaceuticals, the pharmaceutical industry is leveraging 3D printing techniques to manufacture complex, personalised drug delivery systems with controlled release profiles (Greenwood 2024).

The technology also enables rapid prototyping and production of Custom Tools and Devices, enhancing surgical accuracy and perfectly optimised tools for procedures (Anyshape n. d.). Bioprinting, a cutting-edge 3D printing technique, systematically deposits

bioink – liquids or gels containing living cells and growth factors – in an organised manner that mimics natural anatomical shapes. The goal is to enable the production of bioartificial organs or patient-specific living tissues on demand, offering a groundbreaking alternative to address the critical scarcity of donor organs (Greenwood 2024). Recent breakthroughs include the introduction of elastic hydrogel materials for soft living tissue like blood vessels, and cellulose-based inks showing versatility in drug discovery and regenerative medicine (Bedi 2025).

The integration of AI-Powered Advancements with 3D printing is yielding remarkable improvements across healthcare, enhancing design, personalisation and operational efficiency (Jaycon 2025). AI-driven innovation in 3D-printed vascular tissues, for instance, has improved graft success rates and durability by as much as 35% (ibid). AI also plays a vital role in designing novel medical devices, automating manufacturing processes to reduce human intervention and errors, aiding in predictive analytics for error detection and enhancing quality assurance by validating designs for print suitability (Towards Healthcare 2025).

Design for Additive Manufacturing: A Paradigm Shift

Design for Additive Manufacturing (DfAM) is a specialised methodology comprising a collection of rules and best practices that designers and engineers must adhere to for achieving optimal success in 3D-printed part designs. DfAM systematically incorporates critical considerations throughout the design process, including the chosen printing technology, the part's geometry, the specific materials to be used and any required post-processing steps to enhance strength or surface finish (Protolabs n. d.).

A key differentiator of DfAM is its ability to transcend the traditional design constraints inherent in conventional manufacturing methods like milling, casting, or forging. This "shape freedom" opens entirely new possibilities for creating highly complex geometries and enabling true mass customisation at commercially viable costs, which were previously unfeasible (Renishaw n. d.). DfAM significantly facilitates **part consolidation**, a major benefit for medical device manufacturers (ibid). **Lightweighting** is greatly enhanced by DfAM, as it enables the creation of lighter, stronger and more efficient designs through techniques like topology optimisation and the incorporation of special internal structures (eg lattices). These designs can maintain crucial specifications like strength and stiffness while significantly reducing overall weight by using less material (Protolabs n. d.).

> "Life Cycle Assessment studies (…) have shown that 3D printing can provide tangible environmental benefits compared to traditional manufacturing methods."

The rise of Point-of-Care (POC) 3D printing facilities in hospitals marks a significant trend towards decentralised manufacturing. This move is driven by the ability to create patient-specific solutions directly within the hospital setting, which not only improves surgical outcomes but also cuts costs and reduces turnaround times by eliminating reliance on external providers (Jaycon 2025). The increasing accessibility and affordability of 3D printing, combined with its ability to create patient-specific solutions on-demand, enables a shift from centralised, large-scale manufacturing to decentralised, point-of-care production. It has profound implications for improving healthcare accessibility, particularly for underserved populations and enhancing the resilience of medical supply chains during crises by enabling rapid, local production.

The Impact on Sustainable Healthcare

The integration of 3D printing into healthcare extends beyond clinical benefits, offering significant potential to advance sustainable practices. This impact is multifaceted, encompassing waste reduction, the promotion of circular economy principles, the provision of durable precision devices and enhanced energy efficiency.

Waste Reduction and Resource Efficiency

3D printing's ability to enable on-demand production and localised manufacturing significantly minimises the need for large, centralised inventories and reduces

the volume of transportation packaging (Sustainability Directory 2025). By storing designs as digital files rather than physical products, healthcare facilities can eliminate waste from items that expire, become obsolete or are damaged during storage (ibid). Point-of-care (POC) printing, in particular, directly reduces sterile packaging waste associated with the transport and storage of conventional devices (ibid). Furthermore, the precision and customisation afforded by 3D printing lead to better patient outcomes. For instance, patient-specific surgical guides can reduce surgical time and complications (AHA n. d.). By ensuring a perfect fit and function for devices like orthopaedic implants or dental prosthetics, 3D printing indirectly reduces waste associated with failed procedures or ill-fitting devices that would otherwise require multiple attempts or replacements (Sustainability Directory 2025).

Advancing Circular Economy Principles

The concept of integrating circular economy principles into medical 3D printing is gaining momentum. A study demonstrated the feasibility of collecting plastic waste (eg high-density polyethylene (HDPE) water bottle caps from hospitals), shredding, extruding and spooling it into functional 3D printing filaments. This process not only showed significant economic savings compared to commercial options but also resulted in a notable reduction in carbon dioxide (CO2) emissions. The approach directly addresses the growing stream of plastic waste generated by customised, often single-use, 3D-printed medical devices, positioning 3D printing at the intersection of innovation and environmental sustainability (Jreije et al. 2025).

Despite these advancements, challenges remain. Many currently used polymers and resins in 3D printing are non-biodegradable, contributing to long-term environmental concerns (Avanija 2025). Therefore, the development of proper disposal and recycling strategies specifically for 3D-printed medical devices is still an ongoing and critical need (ibid). Paradoxically, the very strength of 3D printing: its ability to create highly customised, patient-specific devices, leads to a new waste challenge. The unique nature of these devices often precludes traditional sterilisation and reuse, making them single use by design, thus generating a new category of medical plastic waste (Jreije et al. 2025). This highlights a critical challenge for achieving comprehensive sustainability.

Precision Prosthetics and Tools: A Sustainable Alternative

3D printing enables the creation of hyper-customised prosthetics that are precisely adapted to an individual patient's anatomy (Quadra 2024). This ensures a snug and secure fit, significantly reducing common issues like pressure sores, skin irritation and improper gait mechanics (ibid). While many 3D-printed items, such as surgical guides or boluses for radiotherapy, are designed for single-use due to patient-specific customisation and contamination risks (Jreije et al. 2025), the technology's

Benefit Category	Specific Impact	Mechanism/Enabler
Waste Reduction	Up to 70% material waste reduction	Additive manufacturing process, precise material deposition
Resource Efficiency	Minimised excess inventory, reduced transport packaging	On-demand production, localised manufacturing, digital design storage
Circular Economy Integration	Feasibility of recycled filaments (eg HDPE), reduced CO2 emissions from recycling	Development of biodegradable/recyclable materials, closed-loop material systems
Energy Efficiency	Lower energy consumption in small-scale production	Operates at lower temperatures, less power-intensive processes
Reduced Carbon Footprint	Substantial reduction in transportation emissions	Localised production, reduced need for long-distance shipping
Cost Savings	Lower material waste, faster prototyping, reduced inventory costs, shorter surgical times	Efficient material use, rapid iteration, on-demand manufacturing, patient-specific planning

Table 1. Environmental and Economic Benefits of 3D Printing in Healthcare

core capability to create durable, patient-specific prosthetics and tools offers a sustainable alternative to the high volumes of generic, often ill-fitting, single-use items (Avanija 2025). The rapid prototyping and modification capabilities inherent in 3D printing reduce the need for multiple design iterations and associated material waste (Quadra 2024).

savings from in-house filament production compared to commercial options alongside a notable reduction in carbon dioxide (CO2) emissions (Mansour et al. 2025). This demonstrates a direct, quantifiable link where environmentally responsible practices (waste reduction, material reuse, lower carbon footprint) simultaneously yield significant economic advantages (cost savings). The investment in sustainable processes is not just

> "Implementing and operating 3D printing services in a healthcare setting requires a highly specialised and multidisciplinary skillset."

Energy Efficiency and Reduced Carbon Footprint

3D printing is recognised for its energy efficiency, particularly in small-scale applications, as it generally operates at lower temperatures and consumes less power compared to energy-intensive conventional production techniques (Avanija 2025). However, it is important to note that large-scale additive manufacturing production can still require significant energy (ibid). The ability for healthcare facilities to produce medical tools and implants on-site significantly reduces the need for long-distance transportation of supplies. This directly translates to a substantial reduction in transportation-related pollution and lowers the overall carbon footprint associated with the manufacturing and distribution of medical products (ibid).

Life Cycle Assessment (LCA) studies, which evaluate environmental impacts across a product's entire lifespan, have shown that 3D printing can provide tangible environmental benefits compared to traditional manufacturing methods (Bahr 2024). These assessments consider factors such as energy use, material consumption and emissions from raw material acquisition through manufacturing, use and end-of-life disposal (ibid). The adoption of sustainable materials and the use of in-situ process monitoring and closed-loop control further enhance AM's potential to advance sustainability by improving process reliability and reducing energy consumption and failure rates (Su et al. 2024).

The economic and environmental benefits of 3D printing are often intertwined. The technology is touted for its cost-effectiveness, reducing material waste, enabling faster prototyping and lowering inventory costs compared to traditional manufacturing (Ortis et al. 2025). A specific study on recycling hospital plastic waste into 3D printing filaments explicitly found cost

an ethical choice but a financially prudent one. This dual benefit – environmental stewardship coupled with economic efficiency, – can serve as a powerful accelerator for the widespread adoption of sustainable 3D printing practices in healthcare. It provides a compelling business case for healthcare institutions and manufacturers to prioritise and invest in green initiatives, as these efforts directly contribute to both their sustainability goals and their bottom line.

Overcoming Challenges and Accelerating Adoption

Despite the transformative potential of 3D printing in healthcare, several significant challenges must be addressed to ensure its widespread and effective adoption. These include navigating complex regulatory frameworks, addressing data security and intellectual property concerns, overcoming material and cost barriers and bridging the existing skill gap. Overcoming these challenges is crucial for fully realising 3D printing's potential to contribute to sustainable healthcare.

Navigating the Regulatory Landscape

The regulatory environment for 3D-printed medical devices is overseen by key bodies such as the European Medicines Agency (EMA) and its Medical Device Regulation (EU MDR), the U.S. Food and Drug Administration (FDA) and the International Organisation for Standardization (ISO) (Lee 2025). The FDA, for instance, regulates the manufacturing process and the final output of 3D printers if it constitutes a medical device, categorising products based on risk levels (Talkington 2022). ISO 13485 specifies comprehensive requirements for quality management systems in medical device production, including those utilising 3D printing (Anyshape n. d.).

A significant hurdle is the continually evolving and often incomplete or non-existent regulatory guidelines for specific medical applications of 3D printing, particularly for point-of-care (POC) manufacturing within hospitals (Talkington 2022). This ambiguity creates substantial uncertainty regarding which parties are responsible for ensuring compliance, their legal liability and what specific regulatory obligations apply when healthcare facilities produce devices under various scenarios (ibid). This lack of clarity can hinder the adoption of sustainable practices, such as in-house recycling or localised production, due to legal and compliance uncertainties (Lee 2025).

Addressing Data Sharing, Intellectual Property and Cybersecurity

The digital nature of 3D printing makes intellectual property (IP) highly vulnerable. CAD files, material selections and build configurations represent valuable trade secrets that can be easily copied, shared, or reverse-engineered by unauthorised parties, leading to patent, trademark and copyright infringement (Banks 2025). The ease of unauthorised reproduction poses significant legal challenges for IP holders (ibid).

As 3D printing systems become increasingly connected within manufacturing ecosystems, they become susceptible to a range of cybersecurity threats. These include network intrusions, unauthorised firmware tampering (which could lead to failed prints or functional sabotage) and data overcollection (Long 2024). A particularly concerning risk in healthcare is the potential for cybercriminals to implement intentional defects into 3D-printed products (eg altering print orientation to reduce strength by up to 25%) or even to hack into printers to alter drug formulas, with potentially life-threatening consequences (ibid). Compliance with data privacy regulations like GDPR necessitates robust safeguards for sensitive patient data (Shafner 2025). These cybersecurity risks can undermine the trust and reliability necessary for widespread adoption, including the implementation of sustainable, digitally-driven workflows.

Material Limitations and Cost Barriers

A significant limitation for widespread adoption is the currently restricted range of suitable biocompatible materials (polymers, metals, ceramics and bio-inks) for medical 3D printing (Healthie n. d.). For instance, common titanium alloys (eg Ti6Al4V) used in implants are much stiffer (110 GPa) than natural bone (10-30 GPa), which can lead to adverse stress shielding effects (China 3D Printing 2025). Furthermore, for bioprinting complex organs, finding the right combination of natural and synthetic polymers for bioinks that mimic native tissues' complexity and functionality remains a difficult and expensive endeavour (Arellano 2022). The limited availability of truly biodegradable and recyclable medical-grade materials also poses a direct challenge to achieving comprehensive sustainability goals in 3D printing (Avanija 2025).

The upfront cost of acquiring advanced 3D printers, particularly industrial-grade systems, and the ongoing expense of specialised medical-grade materials (eg Ti6Al4V powder costing 240 Euro/kg) can be substantial (China 3D Printing 2025). High equipment maintenance expenses (eg over 60,000 Euro per year) further contribute to the overall financial burden, making the technology too expensive for many healthcare facilities to adopt independently (ibid). The significant gap between the actual operating expenses of in-house 3D printing programmes and the amounts reimbursed by insurance payers severely limits their financial viability and scalability (Munteanu 2024). These cost barriers directly hinder the adoption of 3D printing solutions that could otherwise drive significant sustainability improvements.

Bridging the Skill Gap and Fostering Widespread Adoption

Implementing and operating 3D printing services in a healthcare setting requires a highly specialised and multidisciplinary skillset. Personnel need expertise in medical imaging, anatomy/pathology for accurate segmentation, engineering skills for 3D model preparation and a deep understanding of 3D printing hardware and software (Munteanu 2024). The challenge lies in finding enough professionals who possess this unique blend of 3D technology and medical domain knowledge (ibid). This skill gap can slow down the efficient and sustainable integration of 3D printing into clinical workflows. More critically, widespread clinical adoption is hampered by the need for more robust clinical trial data, particularly studies with larger sample sizes and long-term evaluations, to conclusively demonstrate reliability, safety and efficacy and to address existing reliability concerns (ibid). Healthcare institutions must strategically define the ideal scale for their 3D printing programmes (departmental vs. institutional) and implement solutions that manage the entire workflow. Ensuring traceability of models (eg pre-labelling with requisition numbers linked to medical records) is crucial for patient safety and quality control (Pietila 2015).

Conclusion

The advance of 3D printing in the healthcare sector represents a profound technological and operational revolution, offering unparalleled opportunities for personalised medicine and sustainable practices. The inherent additive nature, coupled with localised production capabilities, offers substantial environmental benefits through waste reduction, minimised inventory and a lower carbon footprint, laying the groundwork for a truly circular economy in healthcare.

However, the path to widespread adoption is not without significant hurdles. Regulatory ambiguities, particularly concerning point-of-care manufacturing and reimbursement, create financial and legal uncertainty. The digital nature of 3D printing introduces complex challenges related to intellectual property protection and cybersecurity, demanding robust data security protocols. Material limitations, especially in developing biocompatible and truly sustainable materials with ideal mechanical properties, and the high initial investment costs of equipment remain substantial barriers. Finally, a critical skill gap exists, necessitating specialised training for healthcare professionals in both medical and additive manufacturing domains, alongside the need for more extensive clinical trial data to validate long-term efficacy and safety.

To overcome these challenges and accelerate the integration of 3D printing into mainstream healthcare, several key actions are imperative:

1. **Harmonise and Clarify Regulatory Frameworks:** Regulatory bodies must collaborate internationally to develop clear, comprehensive and adaptable guidelines that address the unique aspects of 3D-printed medical devices, especially for point-of-care manufacturing. This includes defining responsibilities, liabilities and pathways for device approval and post-market surveillance, thereby enabling more sustainable localised production and material reuse.
2. **Establish Robust Reimbursement Policies/ New Business Models:** Healthcare payers and policymakers must work with providers to create fair and consistent reimbursement codes that accurately reflect the costs and value of 3D-printed medical devices and services. This financial clarity is crucial for incentivising investment and scaling in-house printing capabilities, which are key to sustainable healthcare. Healthcare industry also needs to explore new viable business models that enables and caters sustainably to the shift from centralised, large-scale manufacturing to decentralised, point-of-care production.
3. **Strengthen Cybersecurity and IP Protection:** Implement industry-wide best practices for cybersecurity, including network segmentation, strong authentication and encryption, to safeguard sensitive patient data and intellectual property. Legal frameworks must also evolve to effectively protect digital designs and address unauthorised reproduction, ensuring the integrity of sustainable digital workflows.
4. **Invest in Sustainable Material Research and Circular Economy Models:** Prioritise research and development into novel biocompatible, biodegradable and recyclable materials tailored for medical applications. Simultaneously, develop and implement closed-loop recycling and reuse strategies for 3D-printed medical waste, transforming single-use items into valuable resources and fully realising the circular economy in healthcare.
5. **Bridge the Skill Gap through Education and Training:** Develop standardised curricula and training programmes that equip medical professionals, engineers and technicians with the interdisciplinary skills required for medical 3D printing, from imaging and design to printing operations and quality control.
6. **Expand Clinical Evidence and Standardisation:** Conduct more large-scale, long-term clinical trials to generate robust data on the safety, efficacy and cost-effectiveness of 3D-printed medical devices. This evidence is vital for building clinician confidence, informing regulatory decisions and driving broader adoption of solutions that offer long-term sustainability benefits.
7. **Foster Collaboration and Digital Integration:** Encourage greater collaboration between healthcare institutions, technology providers, material scientists and regulatory bodies. Invest in integrated digital platforms that streamline workflows from patient imaging to design, printing and post-processing, ensuring seamless data flow and traceability, which are essential for efficient and sustainable operations.

By strategically addressing these areas, the healthcare sector can fully harness the transformative power of 3D printing, leading to a future where medical care is not only more personalised and effective but also fundamentally more sustainable and accessible for all.

Conflict of Interest

None.

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AI Orchestration in Emergency Radiology – Implementation in the Valencia Health Region

The Valencia Health Region deployed a vendor-neutral AI orchestration system across 29 hospitals to improve emergency radiology. Validated at Hospital General Universitario Dr Balmis, it streamlines triage, accelerates diagnoses and reduces radiologists' workload. The system processes over 5,700 studies daily, delivers results in 1:35 minutes on average, supports EMRAM and DIAM digital maturity goals and is expanding to other imaging specialties.

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key points

- Valencia deployed AI orchestration in 29 hospitals for emergency radiology.
- Hospital Dr Balmis validated the system before regional implementation.
- AI delivers triage results in an average of 1 minute and 35 seconds.
- Over 580,000 radiology studies have been processed since deployment.
- The system aligns with EMRAM and DIAM digital transformation frameworks.

Introduction

The integration of artificial intelligence (AI) into medical imaging is reshaping emergency radiology by improving efficiency, increasing diagnostic precision and accelerating clinical decision-making. As part of a regional strategy to modernise services, the Generalitat Valenciana deployed an AI orchestration system, powered by Idonia, across all 29 hospitals in its healthcare network, serving a population of around five million people. The initiative was intended to ensure consistent radiological services, strengthen workflows and maintain interoperability with existing clinical and IT infrastructures.

The Hospital General Universitario Dr Balmis in Alicante played a central role in validating the system before it was extended to the entire network. The hospital tested its integration into daily practice, ensuring that the system could manage multiple algorithms while allowing clinical teams to retain control over selection and use. Initial implementation focused on algorithms designed to detect bone

fractures and chest pathologies within emergency radiology. Medical images were automatically transmitted to the algorithms, which processed and prioritised cases in real time. By classifying studies as positive, negative or uncertain, the system supported emergency physicians in triaging cases and ensuring timely attention to patients requiring urgent care.

The deployment demonstrated measurable benefits. Automated prioritisation reduced diagnostic review times and eased the workload on radiologists, who could concentrate on complex cases rather than routine negative studies. By providing rapid results and highlighting potential findings, the system enhanced decision-making and improved overall efficiency within the emergency department. The successful validation at Hospital General Universitario Dr Balmis provided the foundation for rapid adoption across the wider regional network.

In addition, the orchestration layer was designed to strengthen workflow transparency. It enabled real-time monitoring of both original and AI-processed images and incorporated an analytics dashboard that allowed clinicians to track performance and refine processes. These functions supported continuous improvement, reinforced clinical confidence in the system and contributed to building a more resilient emergency radiology service.

> "Since implementation, more than 580,000 studies have been processed, with daily averages of around 5,700."

Transforming Emergency Radiology with AI: Faster Triage, Smarter Decisions

The Hospital General Universitario Dr Balmis was the first site in the Valencia Health Region to introduce the orchestration system, providing a model for deployment across the wider hospital network. The hospital faced the challenge of rising patient volumes and increasing demand for rapid diagnostics, which placed considerable pressure on radiologists already working at full capacity. The introduction of automated

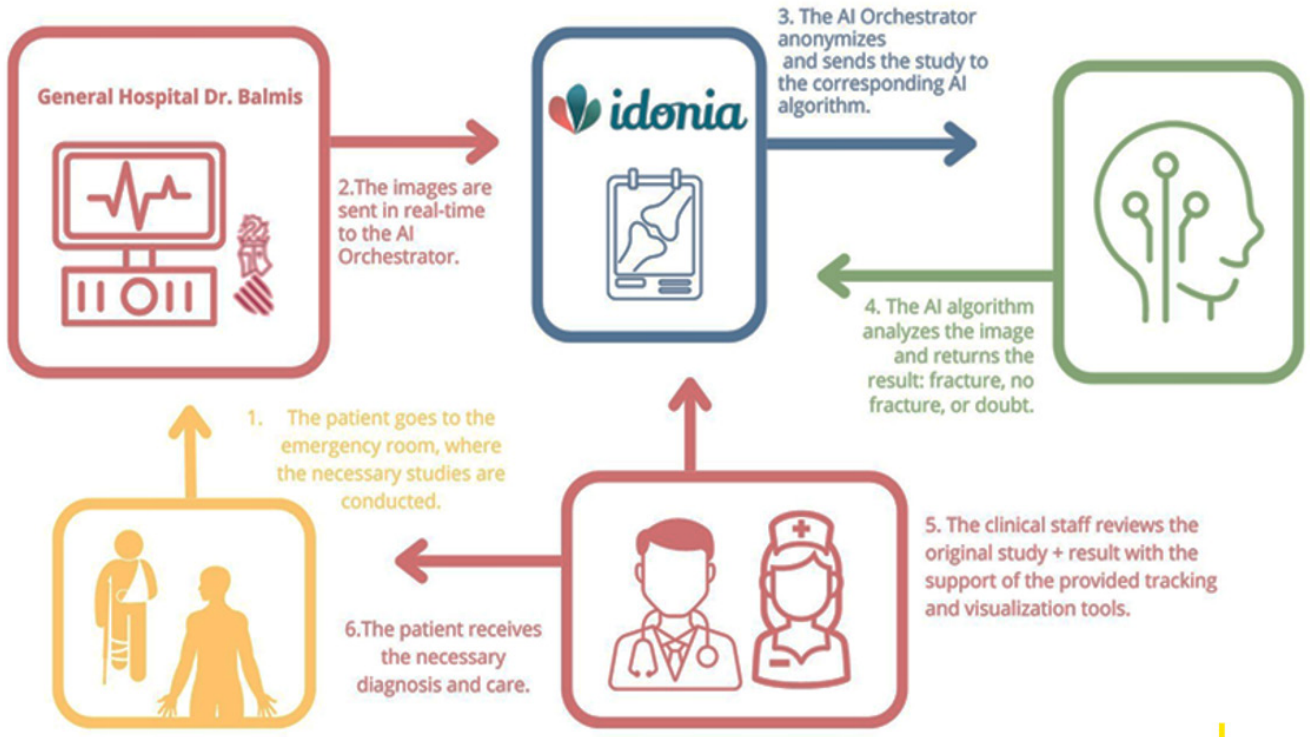

Figure 1. AI-assisted radiology workflow. The diagram illustrates the automated process of transferring, anonymising and analysing radiological studies using AI, showing how results are integrated into clinical workflows.

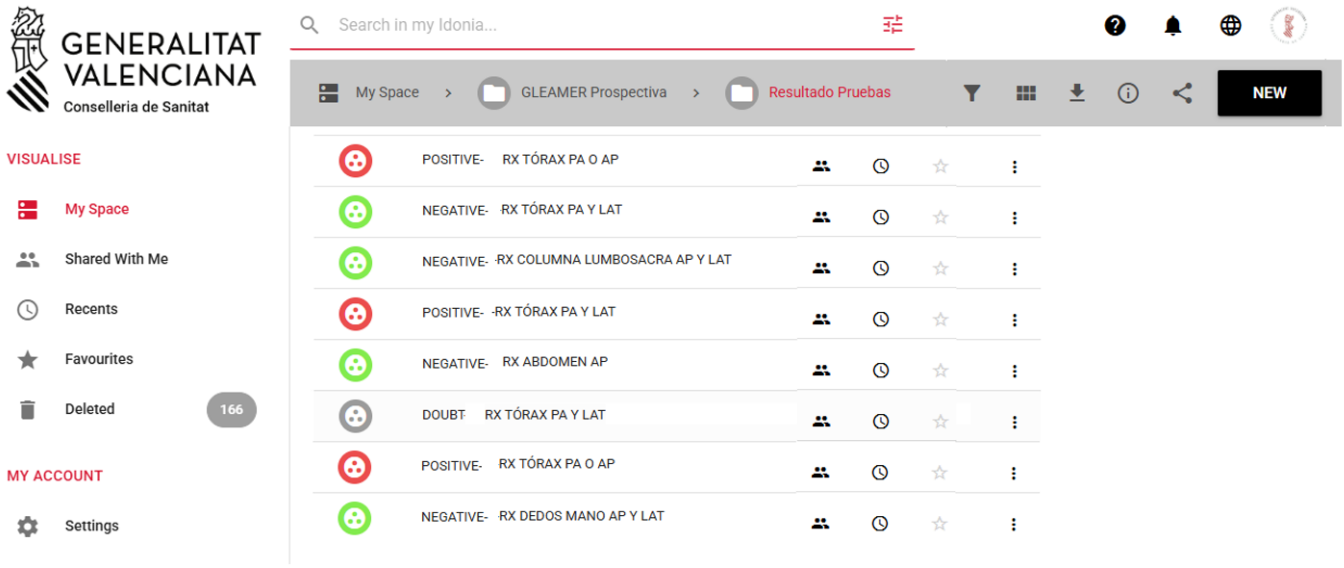

Figure 2. Real-time prioritisation of radiological studies. The diagram shows case classification by urgency level, enabling clinicians to focus on the most critical findings first.

triage aimed to improve efficiency in emergency workflows and ensure timely care for patients with the most urgent conditions, while also supporting continuity with primary care services.

administrators, radiologists, emergency physicians, IT staff and technical teams to ensure alignment with clinical priorities. Traditionally, radiologists were required to manually review large volumes

> "On average, AI-generated results are delivered within one minute and thirty-five seconds, allowing patients requiring urgent care to receive medical attention more rapidly."

At the centre of the implementation was **the objective of enhancing triage and prioritisation in the emergency department.** By integrating directly with the hospital's picture archiving and communication system (PACS), the orchestration layer enabled real-time case classification, allowing critical studies to be identified and reviewed first. This change shortened waiting times for radiological diagnoses, supported faster clinical decision-making and helped reduce delays in patient management (Figure 1). On average, results were available in one minute and thirty-five seconds, enabling more rapid attention to critical patients. The system also added value by highlighting findings that might otherwise have been overlooked, strengthening diagnostic certainty and supporting more efficient use of resources.

The implementation followed a structured but flexible approach designed to limit disruption to hospital operations. It involved close collaboration between

of images, creating bottlenecks and increasing workload. The orchestration system automated this process by classifying studies into positive, negative or uncertain categories (Figure 2). Clinicians were then able to direct their attention to the most urgent cases, reducing cognitive burden and accelerating decision-making.

The impact has been measurable at scale. Since its introduction, the system has processed more than 580,000 studies, averaging 5,700 each day (Figure 3). The automation of triage has reduced the workload of radiologists and emergency physicians, increased diagnostic capacity and enabled departments to manage greater volumes of imaging studies compared to traditional manual workflows.

From an operational perspective, the orchestration system has also helped reduce costs associated with radiology workflows. Automating triage and case prioritisation decreased the time required per study,

leading to greater overall efficiency. Shorter diagnostic delays and smoother patient pathways further strengthened the efficiency gains, producing measurable economic benefits for the health system. These outcomes have reinforced the long-term sustainability of the region's digital transformation strategy.

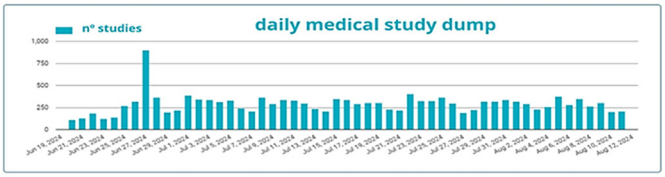

Figure 3. Daily processing of radiological studies. The chart presents the number of studies processed per day, showing the capacity of the system to handle large volumes of imaging data.

Addressing Key Challenges in AI-Driven Emergency Radiology

Despite measurable improvements, embedding AI into emergency radiology workflows required addressing several challenges to ensure effective adoption and long-term impact. Four areas were particularly important: interoperability, data management, data protection and clinical acceptance.

> "The deployment across 29 hospitals was completed in a short timeframe, demonstrating that the orchestration system could be implemented rapidly and consistently across the network."

Ensuring Interoperability and Scalable Integration

Successful deployment of AI required real-time connectivity with hospital PACS, electronic health records (EHR) and other IT systems so that AI-generated insights could be incorporated directly into clinical workflows. A middleware orchestration layer was introduced to serve as a central point of integration between AI algorithms and hospital systems. This avoided one-to-one connections, reduced IT complexity and allowed hospitals to retain autonomy in choosing, testing and switching between different AI models as needs evolved. At Hospital General Universitario Dr Balmis, this included an algorithm designed to detect bone fractures and chest pathologies. Prioritisation results were embedded directly into PACS and radiology interfaces, enabling physicians to view AI outputs without additional steps. Images were anonymised or pseudonymised before being processed and securely transmitted to AI models, with results reintegrated into workflows once deanonymised (Figure 4).

Managing Large Volumes of Imaging Data

High demand for imaging required scalable solutions capable of processing large volumes of studies without disrupting workflows. The orchestration system automated anonymisation, structuring and secure transmission of imaging data. Cloud-based infrastructure provided scalability and high performance, adjusting dynamically to meet hospital requirements and variable demand. As a result, AI-generated outputs were delivered in an average of one minute and thirty-five seconds. The scalable design also supported rapid regional deployment, enabling implementation across three hospitals per week until all 29 hospitals were covered, without compromising performance or service continuity.

Safeguarding Data Privacy and Security

Maintaining strict data protection standards was essential for compliance and clinical trust. The orchestration system incorporated end-to-end security measures aligned with GDPR, ISO 27001, ISO 27017, ISO 27018, SOC 2/3 and Spain's Esquema Nacional de Seguridad (ENS). All images were automatically anonymised before AI analysis, removing identifiers while preserving diagnostic quality. Data transfers were encrypted end-to-end to ensure secure communication between hospital systems and AI models. These measures enabled AI outputs to be embedded into workflows without compromising patient confidentiality.

Supporting Clinical Adoption

For the system to be fully adopted, AI-generated insights needed to be intuitive, reliable and aligned with existing physician practices. Results were therefore embedded directly into established reporting systems, avoiding additional steps for radiologists and emergency physicians. An intuitive colour-coded triage interface

was introduced to highlight urgent cases. Validation phases enabled physicians to compare AI outputs with conventional diagnostics, reinforcing confidence in clinical reliability. A study conducted by the Generalitat Valenciana confirmed the system's effectiveness, reporting positive predictive values of 76.8% for thoracic lesions and 61.3% for bone lesions, with negative predictive values of 83.0% and 95.0%, respectively. These results demonstrated that the system accelerated workflows while maintaining diagnostic accuracy, supporting trust in AI as a complement to clinical expertise. Continuous collaboration with hospital teams ensured that outputs were adapted to real-world needs and reinforced usability.

Scaling AI in Healthcare: Regional Strategy and Future Developments

Beyond addressing immediate implementation challenges, the Generalitat Valenciana has committed to ensuring that AI adoption remains scalable and sustainable across the healthcare system. This strategy is designed to enable the 29 hospitals of the Valencian Community to expand their AI capabilities over time while maintaining clinical integrity and alignment with healthcare priorities.

To achieve this, a structured framework for integration has been developed. It enables hospitals to:

- Flexibly adopt and evaluate AI solutions, with the ability to integrate, validate and switch between algorithms as needed, avoiding dependence on a single provider.
- Strengthen system robustness and risk management by incorporating monitoring and logging mechanisms for real-time anomaly detection, supporting uninterrupted AI-driven workflows.
- Use AI-generated data for continuous improvement by analysing algorithm performance and patient demographics to refine triage processes, optimise workflows and improve outcomes.

The next phase across the regional network will focus on enhancing triage efficiency and broadening AI applications beyond emergency radiology. Planned areas of expansion include neurological and cardiovascular imaging, with the goal of improving diagnostic precision and accelerating treatment pathways. Real-time analytics will also be developed further to generate actionable insights, guide resource allocation and support personalised alerts that improve patient flow. Continuous clinical validation and collaboration with hospital teams will remain central to this approach, ensuring usability, trust and sustainable adoption.

The initial success at Hospital General Universitario Dr Balmis provided the model for wider replication. The deployment across 29 hospitals was completed in a short timeframe, demonstrating that the orchestration system could be implemented rapidly and consistently across the network. This experience underlined the potential of AI-supported workflows to improve efficiency, enhance diagnostic processes and strengthen clinical practice at scale.

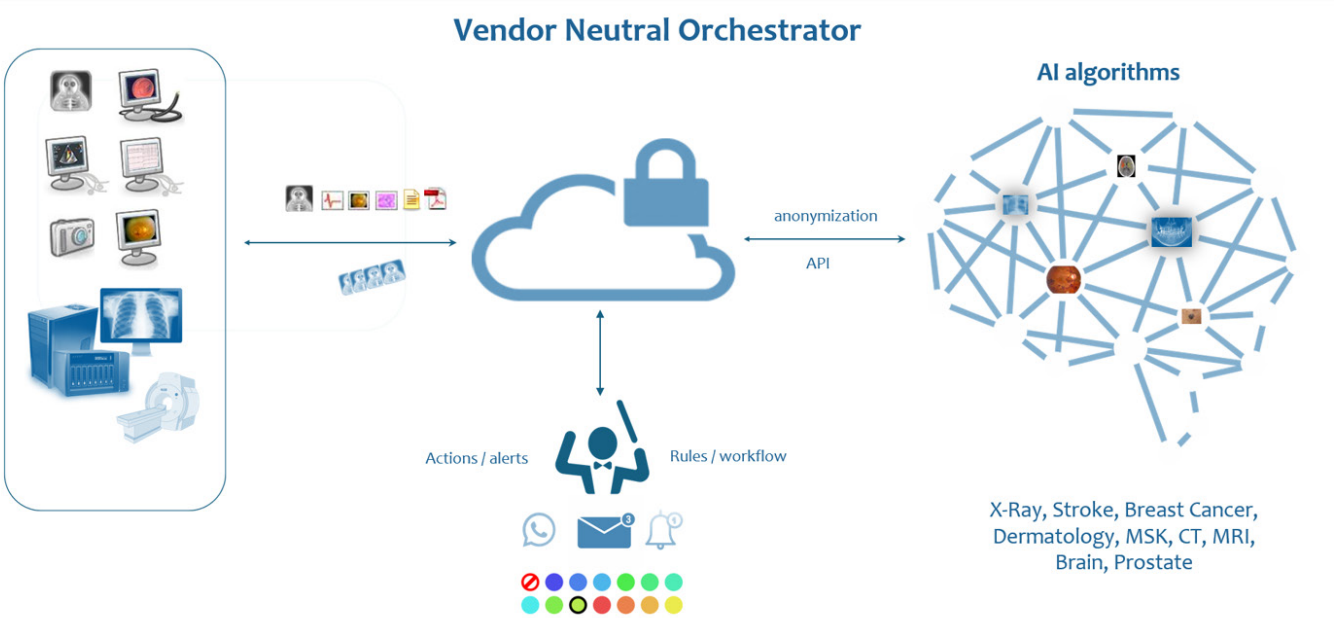

Figure 4. AI orchestration system. The diagram illustrates secure anonymisation of images, submission to AI algorithms and reintegration of results into clinical workflows, highlighting interoperability with hospital systems and cloud services.

The initiative has also been aligned with established international digital maturity frameworks. On the Digital Imaging Analytics Maturity (DIAM) scale, the hospital has advanced towards Stage 5 through systematic use of radiological data and AI-driven insights to optimise workflows. The orchestration approach has contributed to progress towards Stage 7 requirements by enabling predictive analytics that support triage, resource allocation and diagnostic accuracy.

In parallel, integration with the Electronic Medical Record Adoption Model (EMRAM) has advanced the digital positioning of hospitals in the region. Real-time electronic exchange of imaging reports between clinicians and patients fulfils many of the Stage 7 compliance statements. The system also aligns with Stage 5–6 requirements for data integration, supporting interoperability between AI models, PACS and clinical decision-support systems. By facilitating secure image sharing, improving accessibility and enhancing patient-centred imaging, the orchestration system contributes to higher-level EMRAM objectives related to efficiency, safety and quality of care.

These advances strengthen digital governance and foster a more integrated radiology ecosystem. Alignment with Stage 6 of the Analytics Maturity Adoption Model (AMAM) is evident through the incorporation of AI-based recommendations into clinical decision-making, supporting guideline compliance and improving operational and patient outcomes. Looking ahead, the scalability of the orchestration system provides a pathway towards Stage 7, where predictive analytics are used to evaluate standardised care pathways, inform leadership decisions and enable the personalisation of treatment strategies to support equitable health outcomes.

Figure 5. Key functions of the orchestration system. The image highlights features including interoperability, controlled data flow, anonymisation, separation of AI results and dynamic algorithm management, supporting integration of AI into clinical practice.

Why an AI Orchestrator is Essential: The Vendor Neutral Orchestrator (VNO) Concept

With more than 300 CE- and FDA-certified AI algorithms available for medical imaging, integrating multiple solutions into hospital workflows presents considerable challenges. While many AI systems offer PACS connectivity, maintaining separate connections for each algorithm is inefficient and can create additional complexity. An interoperability platform is therefore essential, not only to support AI integration but also to enable secure image exchange, streamline referrals, enhance data analytics and improve accessibility for clinicians and patients.

The orchestration system was developed to act as a single connection point for multiple AI algorithms, reducing IT complexity and limiting the need for infrastructure modifications. Clinicians can activate or deactivate AI models as required, creating flexibility to test, compare and validate different approaches without dependence on one vendor. The system manages interoperability, data flow and infrastructure optimisation, allowing hospitals to integrate AI solutions efficiently (Figure 5).

The orchestration layer is designed as a vendor-neutral solution, allowing healthcare providers to integrate, validate and switch between algorithms from different sources. This approach avoids lock-in to proprietary systems, promotes interoperability and ensures that AI adoption remains flexible and scalable as clinical needs change.

Additional functions include automated anonymisation and rehydration of data. Before analysis, all patient identifiers and quasi-identifiers are removed to ensure compliance with GDPR and other healthcare privacy regulations. Once AI results are generated, data are securely re-associated in a traceable workflow. AI-generated findings are separated from original reports, giving radiologists the opportunity to review and validate outputs before they are included in patient records, which supports trust in AI-assisted diagnostics.

The orchestration system also regulates data volumes to prevent algorithm overload. Direct connections between PACS and algorithms can saturate processing capacity, slowing response times. By filtering irrelevant images and regulating transmission timing, the system prevents bottlenecks and maintains real-time efficiency. The ability to select destination algorithms further increases flexibility,

enabling users to direct studies to specific models based on clinical needs or quality control purposes.

By streamlining AI integration and promoting interoperability, the orchestration model has provided a scalable and secure basis for radiology transformation in the Valencia Health Region. It also contributes to compliance with the emerging European AI Act by supporting transparency, accountability and risk management. The system's monitoring and logging functions make AI-driven decisions auditable, while its data security and anonymisation measures ensure compliance with GDPR. This positions the region to continue advancing responsible and ethical use of AI in healthcare.

Conclusion

The deployment of a vendor-neutral AI orchestration system across the 29 hospitals of the Valencia Health Region has transformed emergency radiology workflows by optimising case triage, accelerating diagnostic review and enhancing clinical efficiency. By embedding AI into decision-making processes, hospitals have been able to reduce response times for urgent cases, allocate medical resources more effectively and lessen the cognitive burden on radiologists, contributing to a more resilient emergency care service.

Beyond its immediate operational impact, the initiative supports broader digital transformation objectives. The AI-driven workflow aligns with international frameworks such as the Electronic Medical Record Adoption Model (EMRAM) and the Digital Imaging Analytics Maturity model (DIAM). It enables advanced data integration consistent with EMRAM Stage 5 and supports the development of predictive analytics in line with DIAM Stages 5–6, strengthening the region's position in the adoption of AI for diagnostic imaging.

Idonia's AI Orchestration Platform has also demonstrated measurable operational and financial value. Automation of triage and prioritisation has reduced workflow costs, increased throughput and improved patient flow. On average, AI-generated results are delivered within one minute and thirty-five seconds, allowing patients requiring urgent care to receive medical attention more rapidly. Since implementation, more than 580,000 studies have been processed, with daily averages of around 5,700. These performance indicators reflect reductions in diagnostic delays, improvements in resource allocation and reduced workload for radiologists, reinforcing the sustainability of AI-driven healthcare transformation in the region.

Future plans include extending AI applications beyond emergency radiology into areas such as neurological and cardiovascular imaging. Further development of real-time analytics and AI-based decision support will enhance diagnostic precision, support workflow optimisation and advance patient-centred care. Continued collaboration with clinical teams and ongoing validation of algorithms will ensure reliability, usability and trust in daily practice.

The initial validation of the orchestration system at Hospital General Universitario Dr Balmis provided the foundation for regional rollout and demonstrated its capacity to be adopted at scale. Its successful expansion across all hospitals in the network has established a model for scalable, interoperable and compliant AI adoption, positioning the Valencia Health Region as a reference point for responsible and sustainable digital transformation in healthcare.

Conflict of interest

None.

STAT PROFILE Prime+®

The Most Clinically Advanced Test Menu for Critical Care Includes–

Creat eGFR Urea ePV iMg MCHC

Prime Plus provides the most clinical value of any blood gas/critical care analyzer profile by adding essential tests for kidney function (Urea, Creatinine, eGFR), plasma volume (ePV), ionized magnesium (iMg) and MCHC.

Creatinine, eGFR, and Urea

Over 50% of patients admitted to the ICU develop some degree of acute kidney injury.[1] Creatinine, eGFR, and Urea monitoring provides indication of changes in kidney function and helps guide therapy to prevent AKI.

Estimated Plasma Volume (ePV)

The plasma volume status of a patient is one of the top priorities in evaluating and treating critical illness including CHF, ARDS, AKI, and Sepsis.[2-4]

Ionized Magnesium (iMg)

Hypomagnesemia is a frequent finding in critically ill patients.[5] Magnesium therapy guided by real time ionized magnesium monitoring has been shown to improve outcome in these patients.[6]

Mean Corpuscular Hemoglobin Concentration (MCHC)

Helps differentiate types of anemia.

Test Menu:

pH PCO_2 PO_2 SO_2% Hct Hb MCHC Na K Cl TCO_2
iCa iMg Glu Lac Urea Creat CO-Ox tBil HbF

nova biomedical
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Advances in Imaging

Affidea neuraCare: Scaling Integrated Neurology Excellence across Europe

Affidea's neuraCare Centre of Excellence in Athens brings advanced diagnostics, world-class physicians, targeted therapies, digital monitoring and embedded clinical trials into one coordinated pathway. Built on shared standards, strong governance and patient-centred design, the model aims to cut time to diagnosis, improve consistency and widen access to innovation. The network will scale across Europe through replicable pathways, interoperable data and ready-to-activate research capability.

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key points

- The pathway integrates prevention, diagnosis, treatment and follow-up.
- Advanced imaging includes 3T MRI, PET/CT and SPECT/CT on one site.
- Subspecialist clinics use unified protocols with MDT review.
- Clinical trials are embedded, with real-world data captured.
- Governance supports a scalable European model with outcome metrics.

Neurological conditions are rising across Europe and placing real strain on people and systems alike. Patients often face long waits, fragmented pathways and the stress of navigating multiple providers. Affidea's new neuraCare Centre of Excellence in Athens offers a different route: one place where advanced diagnostics, specialist clinics, targeted therapies, digital follow-up and access to clinical research come together in a single, coordinated journey. The aim is straightforward—quicker answers, more consistent care and a better experience for patients and families, with clearer lines of sight for referrers and payers.

Why This Model, and Why Now

Many neurology services still work in silos. A person might see several teams in different locations, repeat tests and wait months for definitive imaging or a subspecialist opinion. Conditions such as Alzheimer's disease, Parkinson's disease, multiple sclerosis, epilepsy and complex headache disorders need careful assessment and joined-up management that evolves over time. NeuraCare's answer is a network of Centres of Excellence that bring subspecialist expertise, advanced diagnostics and research into a single, well-governed pathway. The standards are shared across sites so care feels consistent, but services remain close to home.

Athens as the Flagship

The Athens centre sets the pattern for what follows. Purpose-designed over two floors, it provides the full arc of care—from prevention and screening through diagnosis, treatment, digital monitoring and research participation. The service spans neurological consultations, digital cognitive assessments and a complete laboratory, supported by a comprehensive imaging suite featuring 3T MRI, PET/CT and SPECT/CT. Neuropsychology, neurological botox and therapy reviews are part of the treatment options,, reducing the need for multiple visits to different sites. Telehealth follow-ups and structured remote monitoring help teams keep in touch between appointments, bringing people back in promptly when needed. The centre

also serves as a research hub, so eligible patients can be offered appropriate trials within the same pathway.

A Pathway That Starts Early

The pathway begins before symptoms peak. Awareness, prevention and risk assessment sit alongside genetics and lifestyle counselling where appropriate. Neurocognitive and neuropsychological testing builds a baseline. From there, sensible sequencing across neurophysiology and cardiac testing where indicated, ultrasound and advanced imaging helps clinicians reach a diagnosis earlier and with more confidence. Laboratory work and, when needed, lumbar puncture complete the picture. Multidisciplinary meetings review complex cases and agree a personalised plan with clear follow-up points. The result is a journey that is easier to understand, quicker to navigate and simpler to measure.

Technology That Serves Decisions

Technology supports the clinical judgement rather than replacing it. High-performance imaging is run under standardised protocols. Data governance is built in, with structured capture and harmonised reporting so teams can benchmark, learn and improve. The priority is to turn information into timely decisions: faster detection, better selection of therapy and well-timed adjustments over the long term.

Research as Part of Care

Clinical research is embedded, not bolted on. The Centre of Excellence is set up to run regulated trials with dedicated staff and clear processes for consent, safety and data quality. That makes study start-up faster and patient experience simpler. It also means more people can access innovation early, particularly important in central nervous system conditions where the pipeline is evolving quickly. Evidence generated in practice can be fed back into the pathway, helping teams refine what they do.

Governance, Standards and Measurement

A shared governance framework keeps the model coherent as it grows. Subspecialty leaders oversee imaging, neurology and nuclear medicine; complex cases are discussed in MDTs; and peer review supports consistency. Pathway design, imaging protocols, reporting and therapy choices are standardised and auditable. In practice, this makes quality visible. Time to diagnosis, time to treatment, patient-reported experience and safety indicators can be monitored and acted on. For commissioners and

> “One place where advanced diagnostics, specialist clinics, targeted therapies, digital follow-up and access to clinical research come together in a single, coordinated journey.”

payers, it provides confidence that faster access and broader reach go hand in hand with robust oversight.

People, Skills and Teams

Centres of Excellence are also centres for learning. Clinicians can combine high-quality care with research and education, take on protocol leadership and contribute to multi-centre studies. Shared standards and peer networks support good practice and reduce unwarranted variation. From a management point of view, engaged teams are easier to retain, services are more resilient and patients benefit from continuity.

Designed Around Patients and Families

Experience is more than a nice-to-have in neurology. The Athens layout favours calm spaces and clear wayfinding. Operationally, the single-journey design reduces multiple separate appointments and long gaps between steps. Education, counselling and support groups are part of the offer, and digital tools provide a safety net between visits. Families and caregivers get predictable schedules and clear information, while joined-up records pull assessments, imaging and lab results into one coherent view for personalised care over time.

Policy Context and National Signalling

At the inauguration, Greece's Minister of Health, Adonis Georgiadis, framed the centre as both a vote of confidence in the health system and a prompt for further innovation. He underlined that pioneering services in neurology bring hope to patients and can lift standards through healthy competition. The message is clear: integrated, high-quality models that invest in capability are aligned with national priorities and can help move the system forward.

> "Today is a landmark day for health in Greece. As we celebrate two decades of innovation and quality, we inaugurate the first Centre of Excellence in Neurology in our country and Europe. Our mission remains to bring science closer to people and to build the future of healthcare today."
>
> **Theodoros Karoutzos, CEO of Affidea Greece**
>
> "This is not just another medical facility, it is true care as it should be. We inaugurated a vision for the future of neurological care. Affidea neuraCare is being built on unified standards, strong collaborations in research and technology, and a patient-first philosophy. Our centres will bring earlier and more accurate diagnosis, innovative therapies and faster access to life-changing research."
>
> **Professor Marios Politis, Chairman of Affidea neuraCare Europe**
>
> "Today, neurological conditions affect one in six Europeans and demand is growing faster than most health systems can respond. NeuraCare was designed to change this trajectory. We are building fully integrated pathways, from prevention and early detection to advanced treatments, clinical trials and long-term monitoring, all delivered within a single, seamless patient journey. NeuraCare is not just a new service line, it is a new model of care."
>
> **Dr. Charles Niehaus, Executive Director for Affidea Group**

Growing the Network Across Europe

The plan is to expand neuraCare to major European cities, keeping the same standards while adapting to local referral patterns, funding and workforce reality. Regional satellites and digital clinics can extend reach without losing pathway fidelity. The architecture is built for replication: shared governance, reusable training, interoperable data and consistent measurement. For systems, it offers scale without starting from scratch. For patients, it brings specialist care closer to home.

What Success Looks Like

Early success will be visible in the rhythm of the pathway: faster triage, shorter time to diagnosis, and treatments started at the right moment for the right patient. Patient-reported experience should reflect a smoother journey and better clinical outcomes. Safety signals must stay strong and prompt quick review when needed. The research portfolio should deepen as more eligible patients are offered trials, with lessons applied back into everyday care.

There are qualitative markers too: active MDTs, confident referrers, families who feel informed and supported, and stable teams as the model grows. As more centres open, the real test will be consistency across sites while allowing for local nuance. That is where shared governance and steady measurement make the difference.

A Scalable Blueprint

NeuraCare is intended as a blueprint rather than a single flagship. By uniting advanced diagnostics, specialist expertise, therapies and trials under one roof – and extending that roof through digital and satellite models – the approach aims to deliver earlier diagnosis, more consistent treatment and well-coordinated follow-up at scale. If it holds course, patients will find neurology care that is faster and clearer, clinicians a setting that supports excellence, and systems a model that balances access, quality and value.

“NeuraCare is intended as a blueprint rather than a single flagship.”

Conflict of Interest

Spotlight articles are the sole opinion of the author(s), and they are part of the HealthManagement.org Corporate Engagement or Educational Community Programme.

Digital Transformation

Global EHR Trends: KLAS Insights on Market Expansion and Clinician Experience

Global EHR adoption surged in 2024, yet clinician satisfaction remains uneven. KLAS data reveal high vendor activity and strategic gains in countries like France, Brazil and Saudi Arabia. However, only the Middle East aligns infrastructure, training, governance and personalisation to deliver strong EHR experiences. To unlock value, healthcare systems must prioritise user engagement and continuous performance improvement over procurement volume alone.

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key points

- Global EHR contracts rose in 2024 but impacted fewer hospitals than in past years.
- France, Saudi Arabia and Brazil led market activity with diverse vendor engagement.
- Clinician satisfaction varies widely, with the Middle East scoring highest globally.
- Training, governance and infrastructure gaps drive dissatisfaction in many regions.
- Personalisation boosts EHR value but remains underused outside the Middle East.

Healthcare systems worldwide increasingly rely on electronic health record (EHR) optimisation, building on the foundation of digital maturity established through earlier implementations. Two recent KLAS reports, one assessing the acute care EHR market globally and another exploring clinician satisfaction across both acute and non-acute settings, offer critical insight into how EHR investment aligns with operational and clinical outcomes. Together, these reports provide a composite picture of EHR progress in 2024–2025, combining data on market dynamics with the real-world experiences of over 52,000 clinicians in 38 non-US organisations.

A Shifting Landscape in EHR Procurement

KLAS validated 246 new EHR contracts in 2024, impacting 550 hospitals and over 122,000 inpatient beds. This represents a five-year high in the number of contracts, despite a five-year low in total hospitals impacted—indicating a trend towards smaller-scale, decentralised procurement. Fewer large-scale

regional decisions were finalised than in 2023, yet multiregional vendors such as Dedalus, Epic and InterSystems continued to gain ground.

Dedalus maintained its market leadership with 24 decisions impacting over 21,000 beds, particularly in France, Germany and Austria. Epic expanded its reach in Canada and Singapore, while InterSystems saw its strongest year since 2020, winning contracts in the Middle East, Asia and Latin America. In the UK, Epic, MEDITECH, Oracle Health and Nervecentre all won new public sector contracts. MEDITECH also gained new clients in Oceania, Latin America and Africa. Vendors such as Aosta and TrioTree expanded in India and beyond.

Market activity was particularly strong in France, the UK, Saudi Arabia and Brazil. In Europe, France led with both public and private sector contracts. In the Middle East, Saudi Arabia accounted for the largest public contract—Cloud Solutions' VIDA platform was selected by a cluster of 21 hospitals. In Latin America, Philips and MV led new signings, particularly in Brazil. Meanwhile, IQVIA and InterSystems increased their footprint in Southeast Asia and Costa Rica, respectively.

Regional Drivers and Procurement Strategies

Market dynamics in 2024 were shaped not just by vendor performance, but by distinct regional procurement strategies and evolving national health priorities. France, for example, saw contracts split between multiregional vendors like Dedalus and local firms such as Nexus AG and Numih France, reflecting a hybrid procurement model.

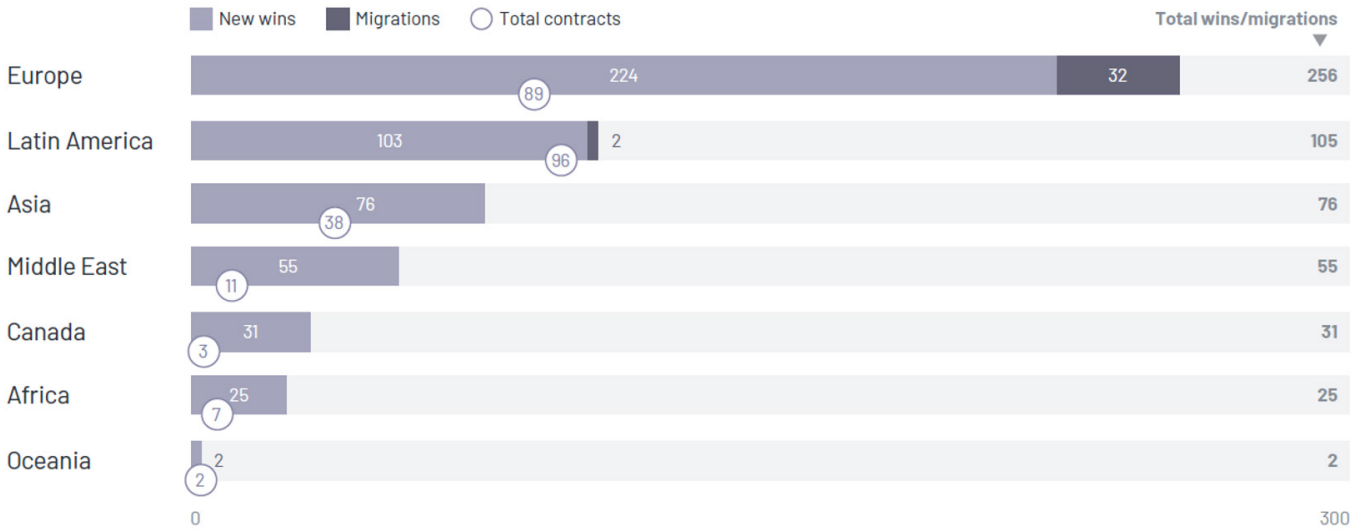
> "Procurement alone is no longer a sufficient metric for success."

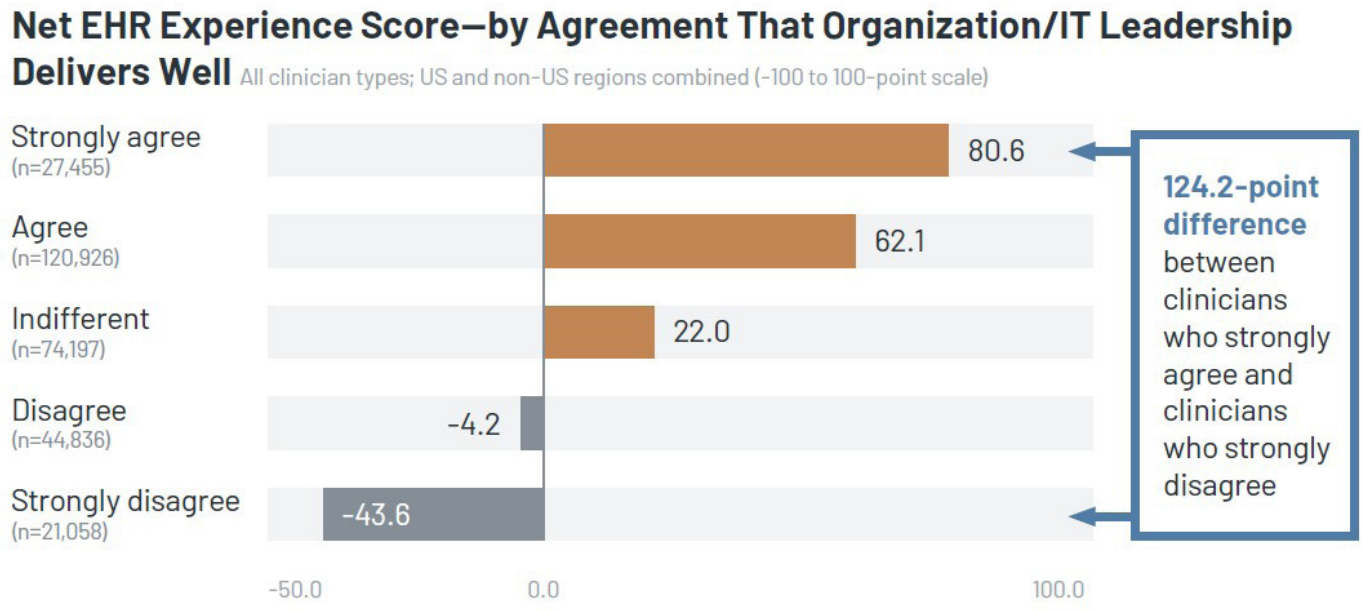
In Saudi Arabia, the drive to realise Vision 2030 has stimulated investment in digital health infrastructure, resulting in the largest public contract of the year. Similarly, the UK continues to pursue regional upgrades, with Epic, MEDITECH and Oracle Health securing contracts.

India showed a growing appetite for scalable solutions with strong local vendor participation, while Brazil reinforced its status as Latin America's most active EHR market, led by Philips and MV. Elsewhere in Latin America and Southeast Asia, InterSystems and IQVIA made gains.

A notable trend in 2024 was the decrease in large-scale regional procurements—down nearly 20% from 2023. This shift towards more localised and tailored EHR strategies reflects greater digital maturity and a preference for autonomy over one-size-fits-all deployments.

2024 Hospital Wins & Migrations—by Region Inpatient hospitals





Note: Data comes from all clinician feedback collected by the Arch Collaborative, not just the 38 non-US organizations examined in this report.

From Adoption to Impact: Clinician Satisfaction Lags Behind

Despite this expansion, the clinician experience with EHRs remains uneven. KLAS' 2025 Global EHR Satisfaction report reveals stark disparities in Net EHR Experience Scores (NEES), which measure clinician perceptions of EHR usability, efficiency and impact on care. The Middle East tops the list with a NEES of 75.4, while Canada (27.6), Oceania (23.6) and Europe (7.3) trail far behind.

Net EHR Experience Scores (NEES), measured on a scale from -100 to 100, illustrate these disparities. The Middle East leads with a score of 75.4, far ahead of Canada (27.6), Oceania (23.6) and Europe (7.3). These scores reflect clinicians' overall perceptions of system functionality, efficiency and impact on care. The marked contrast underscores the importance of a well-coordinated strategy involving infrastructure, training and governance to elevate EHR usability and acceptance.

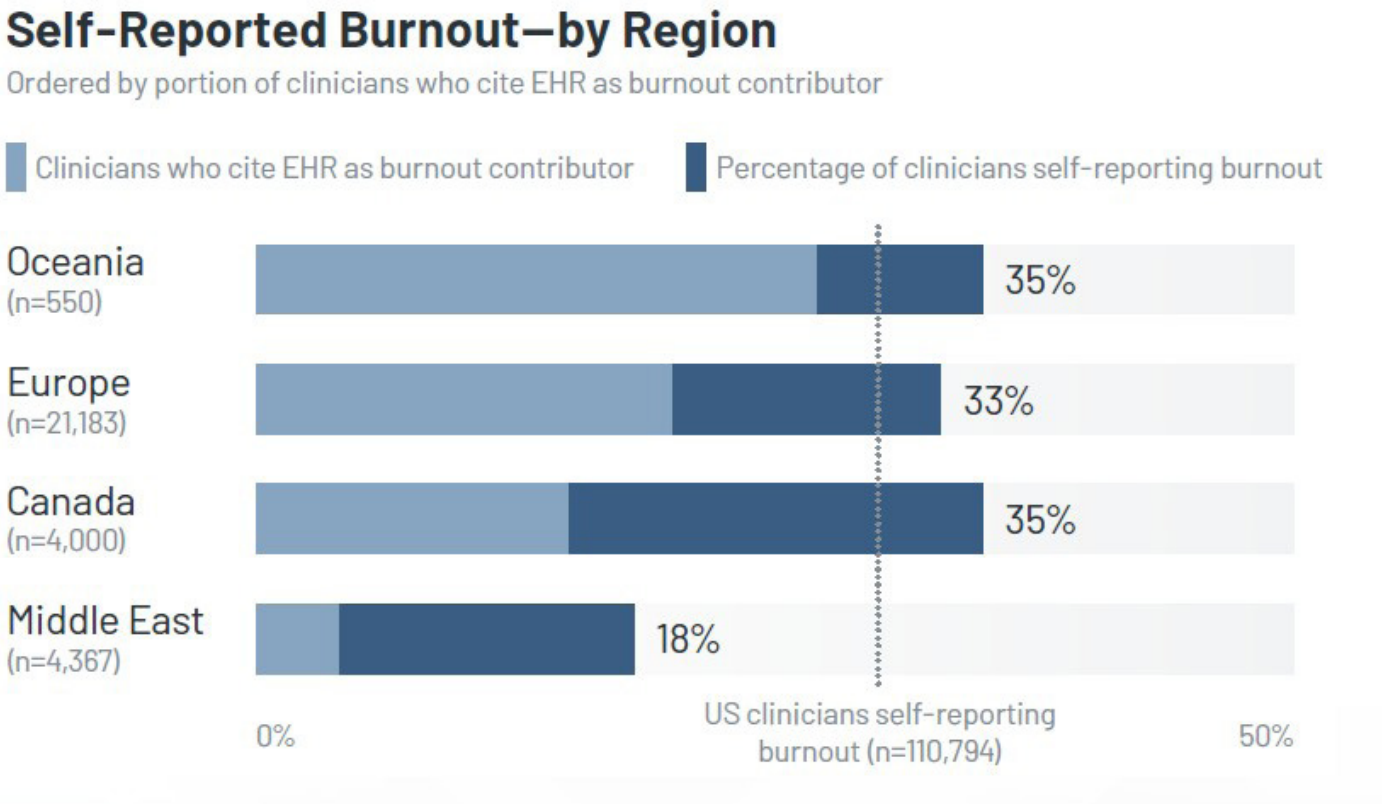
> "Clinicians receiving 11 or more hours of onboarding are significantly more likely to report positive EHR experiences."

The Middle East stands out for achieving the highest level of clinician satisfaction with EHR systems. Its strategic focus on foundational infrastructure, tailored education programmes and inclusive governance mechanisms sets a strong precedent for other global health systems. In contrast, Europe, Canada and Oceania report more modest satisfaction scores, often hampered by inconsistent performance, limited training and poor communication between clinicians and IT leadership.

The data also highlight that without ongoing measurement of EHR impact, organisations may miss key opportunities to align their systems with clinician needs. Proactively tracking satisfaction helps identify problem areas and inform future improvements. In regions failing to assess performance systematically, gaps in experience and functionality can persist unnoticed.

Infrastructure: The Foundation for Success

Reliable infrastructure is a non-negotiable prerequisite for clinician satisfaction. Eighty percent of Middle



Eastern clinicians reported dependable systems with fast response times, compared to just 64% in Canada and 50% in Europe. Issues such as delayed login times, Wi-Fi dropouts and system slowdowns hinder clinical workflows, amplify stress and reduce time available for patient care.

onboarding are significantly more likely to report positive EHR experiences.

Best practices include role-specific instruction, hands-on simulations and ongoing refreshers tailored to evolving clinical workflows. Yet, many healthcare

> "Burnout remains a common issue, cited by about one-third of clinicians globally."

In high-performing regions, regular system maintenance, proactive monitoring of performance metrics (eg login and load times), and communication about scheduled downtimes help prevent disruptions. Where such practices are lacking, even best-in-class EHR systems can fail to deliver value.

Training: A Strategic Investment, Not a Cost Centre

Effective EHR training correlates strongly with clinician satisfaction. In the Middle East, 90% of clinicians said their training was sufficient, compared to 47% in Canada, 43% in Europe and 56% in Oceania. Clinicians receiving 11 or more hours of

systems reduce training investment to manage short-term costs, unaware of the downstream impacts on usability, burnout and turnover. For retention, workflow-specific training is particularly effective—it boosts user confidence and improves perceptions of system efficiency.

Governance: Listening to Clinicians

Governance frameworks that include clinician input consistently yield higher satisfaction. In the Middle East, 87% of clinicians reported that their leadership provided effective support for EHR implementation and optimisation. In Canada, Europe and Oceania, that number drops below 50%.

When clinicians are excluded from decision-making, they report feeling disempowered and disconnected. Poor governance leads to misaligned system updates and a lack of transparency. By contrast, layered governance—including executive, departmental and clinician voices—promotes shared ownership and builds consensus around system changes.

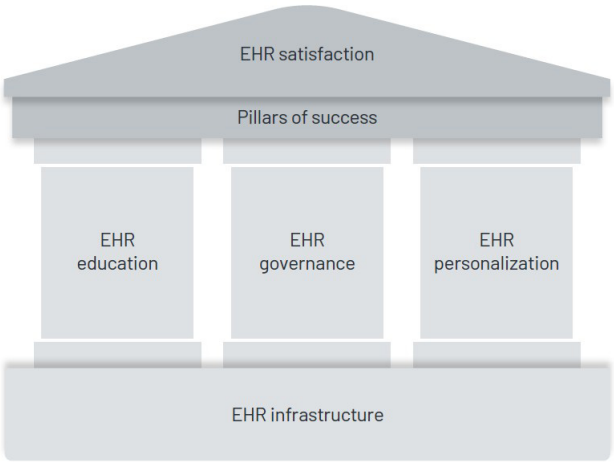
> "Personalisation remains an untapped opportunity in many regions."

Good governance also enhances communication. Keeping clinicians informed of system upgrades and training opportunities encourages engagement and helps avoid resistance. Where governance supports shared strategy, alignment between clinical needs and system evolution is more likely.

Personalisation: Underused, High-Impact Tools

Personalisation remains an untapped opportunity in many regions. Tools like shortcuts, templates, macros and customised layouts significantly enhance daily workflows. In the Middle East, 86% of clinicians use personalisation features; in Canada, Oceania and Europe, fewer than 55% do.

These tools not only save time but restore a sense of control over the digital environment. Low adoption is often due to limited awareness and insufficient training. Embedding personalisation into initial and ongoing education, as well as tracking feature usage, can amplify benefits. Furthermore, identifying high-performing users can help organisations spread best practices across clinical teams.



Burnout: A Global Challenge, Unevenly Addressed

Burnout remains a common issue, cited by about one-third of clinicians globally. While EHR systems are not the sole cause, poor usability and unreliable infrastructure exacerbate stress. In Oceania and Europe, clinicians frequently blame the EHR for workload issues and reduced job satisfaction. In the Middle East, EHRs are less frequently cited as contributors—suggesting that system reliability and support structures can mitigate burnout.

Addressing burnout requires coordinated strategies that blend infrastructure improvements with education and user engagement. When clinicians feel supported and empowered to use their EHR effectively, the system becomes a tool for care delivery, not a barrier.

The EHR House of Success: A Blueprint for Improvement

KLAS advocates for a structured approach to improving EHR satisfaction, known as the "EHR House of Success." This model includes a solid infrastructure foundation, supported by the pillars of education, governance and personalisation. Each component must be addressed in concert, as weaknesses in one area can undermine gains in another.

To replicate the success seen in the Middle East, other healthcare systems should begin with infrastructure audits and establish rigorous performance monitoring protocols. Next, they must invest in comprehensive education programmes tailored to diverse clinical workflows. Governance structures should be revised to ensure meaningful clinician participation, and personalisation should be encouraged as a routine aspect of system interaction.

Regular feedback collection via tools like the Arch Collaborative EHR Experience Survey provides actionable insights for targeted improvements. By tracking satisfaction trends and correlating them with operational changes, organisations can continuously refine their EHR strategies.

Conclusion

The global outlook for EHRs is one of expansion tempered by uneven outcomes. Procurement alone is no longer a sufficient metric for success. True digital transformation hinges on aligning systems with the needs of their users. The Middle East sets a compelling example: by investing in infrastructure, education, governance and personalisation, it has achieved both widespread adoption and high clinician satisfaction.

Healthcare systems across the globe should take note. A well-implemented EHR is not just a digital tool; it is a strategic asset that can reduce burnout, enhance workflows and improve care. Achieving this potential requires more than technology. It demands leadership, collaboration and a sustained commitment to clinician experience.

Conflict of Interest

None.

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RAYS OF KNOWLEDGE

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How to Build Trustworthy Digital Health Initiatives?

Trust is essential for successful digital health initiatives. It does not emerge spontaneously but demands deliberate, targeted efforts. A four-step approach (understand context, identify levers, implement trust indicators and refine actions) supports practical implementation. With a comprehensive understanding of user trust and traits of trustworthy initiatives, it is important to shift from abstraction to practical action using a stepwise method that delivers tangible benefits and keeps trust from remaining theoretical.

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key points

- Trust is vital for the acceptance of digital health initiatives and the broader digital transformation of health systems.
- Frameworks define principles that support the development and implementation of trustworthy digital health initiatives.
- Trust performance indicators enable ongoing evaluation and improvement of initiatives.
- Building trust demands proactivity, leadership, resources, system thinking and continuous action.

Trust as a Foundation for Digital Transformation of Health Systems

At the 78th World Health Assembly in May 2025, Dr. Tedros, Director-General of the World Health Organization (WHO), highlighted the importance of trust for the development of digital health systems (WHO 2025a). In the same vein, WHO Europe and the European Observatory on Health Systems and Policies moved trust into the spotlight of the health policy agenda (McKee et al. 2024). At the national level, numerous digital health strategies and applicable legislation on data sharing underscore the importance of trust for the successful implementation and uptake of health data sharing infrastructures, artificial intelligence in medicine, medical and health applications, and national electronic health record systems, to mention a handful of examples (WHO 2025b; Zavattaro et al. 2024). The underlying thinking is that user trust is necessary to support both the implementation and the use of these initiatives. This is particularly critical in the health domain, where these initiatives involve the handling of sensitive personal data.

Mirroring the importance of trust for the acceptance of digital health initiatives and the broader digital transformation of health systems, researchers explored the conceptual underpinnings of what users perceive as a trustworthy digital health initiative. Building on that work, we are currently in the transition phase from concept to practice answering the question: *How can we build trustworthy digital health initiatives?*

Trust is widely considered a fuzzy concept, difficult to grasp and even more challenging to operationalise within complex digital systems. It is a relational, context-dependent and inherently complex concept which contributes to the absence of a universally accepted definition (Hardin 2002). One way to describe is as "a bet about the future contingent actions of others", a formulation that underscores the central role of time in trust dynamics (Sztompka 1999). Comparative research shows that building trust largely depends on information related to:

a.) past experiences with the actors or the initiative in question,

b.) present perceptions of the digital health initiative's potential to fulfil what it is expected to deliver, and

c.) anticipated beneficial outcomes resulting from that trust (Gille 2023).

While we all have a personal understanding of what trust means for us–shaped by our culture, upbringing and life experiences–it can be challenging to describe trust in complex and abstract systems such as health data sharing for primary and secondary use, or AI in medicine. An additional layer of complexity emerges when trust is examined not only at the individual level, but also at the community or population level, such as public, patient or professional trust.

which comprises ten principles that the public associates with trustworthy health data sharing (Zavattaro et al., 2024). Each of these principles contributes to fostering public trust in health data sharing.

- **Agencies of Accountability:** Identifying agencies accountable for the use of health data.
- **Autonomy of Choice:** Granting individuals control over their health data.
- **Benefit in Health Data Sharing:** Identifying personal or public benefits of the initiative.
- **Communication with Data Subjects:** Actively informing individuals on the use of their health data.
- **Data Traceability:** Ensuring transparency in how health data is used.
- **Deidentification of Health Data:** Removing personal identifiers before sharing data.
- **Privacy Protection:** Protecting individuals' privacy and health data confidentiality fosters public trust in health data sharing.
- **Public Information:** Informing citizens on the initiative through government-led public outreach.
- **Security:** Protecting health data from breaches and misuse.
- **Time:** Allowing individuals a period of reflection before deciding to share their data.

"Trust is widely considered a fuzzy concept, difficult to grasp and even more challenging to operationalise."

To make trust a useful concept for health policymaking, health system governance, hospital management or the healthcare industry broadly, researchers have developed conceptual trust frameworks. Based on interviews with users–asking, for example, *"What makes an AI application trustworthy?"*–these frameworks typically describe principles that users associate with trustworthiness, such as data security, privacy protection and accountability, as well as effects resulting from users' trust, for instance, the adoption of an AI application in practice. Therefore, such frameworks are highly valuable for describing the causes and effects of trust within a specific context and can be used as starting points for operationalising trust-building principles within digital health initiatives. One example is the "Public Trust in Health Data Sharing" framework,

Several other trust frameworks exist that describe, for example, trust in AI, data spaces, electronic health record systems, medical apps or the health system in general (Daniore et al. 2024; Gille 2023; Haasteren et al. 2019; Papadopoulos et al. 2024; Starke et al. 2025).

Operationalising Trust-Building Principles in Digital Health Initiatives

When using a trust framework to operationalise trust-building principles in the governance process or architecture of a digital health initiative, we propose the following steps based on our previous and ongoing research on trust in health systems in the context of data use and policy.

To bring trust-building principles into practice, we need to take a systems-thinking approach (Finegood & Yakimov 2024). Trust-building must be considered a holistic activity orchestrated simultaneously on several levels. Research shows that trust-building requires strong executive leadership, resources and continuous engagement by those aiming to build trust (Gille et al. 2025b). We cannot build trust through a one-off action.

Firstly: Understand Your Context

We need to understand the actors involved–i.e. who is trusting whom–to focus our actions on the right target audience and ensure that the trust framework we use is appropriate. For example, when we apply a trust framework describing physicians' trust in AI applications in medicine, but aim to build a trustworthy initiative for patients, the framework might be of limited relevance. Eventually, conceptual clarity and precise understanding of the context, including the actors involved, are imperative. If we do not know the kind of trust in question–who is expected to trust whom, and which are the actors involved and influencing the trust relationship–any following efforts to build trust are, at best, short on luck, if not useless. Conceptual imprecision has further implications on the ability to comprehensively evaluate trust-building activities, as any type of measurement needs a solid conceptual basis (Streiner et al. 2015).

Secondly: Know Your Levers

When considering the resources we have at hand and what is feasible within a given timeframe, we should map the available levers and options to operationalise each trust-building principle. Usually, there is a set of different levers to operationalise trust-building principles in the context of digital health initiatives. These include, among others, the following areas: communication; digital literacy; governance; law and regulation, and technology.

Data security is widely understood as a vital trait of a trustworthy digital health initiative. It is considered a key trust-building principle: when we see that our data is secure, we are more likely to trust such initiative. The National Cybersecurity Center of Excellence of the U.S. Department of Commerce describes data security as "the process of maintaining the confidentiality, integrity and availability of an organisation's data in a manner consistent with the organisation's risk strategy. Before an incident happens, companies must have a security architecture and response plan in place. Once an incident occurs, they must be able to detect the event and respond accordingly. After the incident, the company must be able to recover effectively and efficiently" (National Cybersecurity Center of Excellence 2025). The application of the five levers to the trust-building principle of 'security' within a digital health initiative is described in Table 1. These actions are provided for illustrative purposes only, and have been deliberately selected and simplified by the authors to demonstrate the underlying reasoning.

The same exercise should be undertaken with all trust building principles described in a given trust framework to make sure that each principle is comprehensively operationalised and deeply embedded within the architecture of the digital health initiative. Prioritisation of trust building principles in a resource scarce environment is necessary.

> "Trust-building is not a one-off action; it requires continuous engagement and adjustment."

That said, current research usually neglects this economical constrain which potentially undermines trust building efforts from the outset. One approach to prioritisation is to conduct a ranking exercise with the user community. Such insights can potentially help to conclude which actions needs to be prioritised (Gille et al. 2025a).

Thirdly: Implement Trust Performance Indicators

Following the operationalisation of trust building principles, we want to understand the extent to which the trust building activities achieve their intended purposes. Evaluating their performance is vital to monitor shifts in user trust, enabling targeted resource allocation and evaluating the effectiveness of trust building principles altogether. Without a robust performance assessment methodology in place, there is a risk that trust-building actions may be undermined by insufficient insights and potentially misaligned resource allocation.

In trust research, population surveys are traditionally used to understand levels of trust (Taylor et al. 2023).

Lever to operationalise data security	Objective	Exemplary actions
Communication	*Communicate to all stakeholders the risks associated with data sharing and the measures implemented to ensure data security (Daniore et al. 2024)*	- **Communicate how data is collected, stored, shared and protected** - **Explain security practices, including potential risks and their limitations** - **Provide timely notifications of data breaches and security policy changes**
Digital Literacy	*Empower stakeholders to manage health data securely and responsibly (Borges do Nascimento et al. 2025)*	- **Deliver training programmes for healthcare workers on secure data and cyber hygiene practices** - **Implement gamified learning tools to enhance engagement and promote understanding of secure behaviour** - **Promote privacy literacy to enable individuals understand their data rights and how to exercise them**
Governance	*Establish oversight and accountability mechanisms for enforcing data security policies. (Blasimme & Vayena 2020)*	- **Define clear roles and responsibilities for data stewardship, including designated Data Protection Officers** - **Establish multistakeholder governance bodies to oversee data security** - **Develop auditing and reporting mechanism to regularly assess security performance and compliance with established standards**
Law & Regulation	*Establish and enforce regulatory frameworks that define binding standards for data security (Zavattaro et al. 2024)*	- **Comply with national and international laws** - **Comply with national and international data security standards** - **Comply with data ethics frameworks**
Technology	*Implement technical safeguards to protect data from illegitimate access, damage or manipulation (Kisekka & Giboney 2018)*	- **Employ end-to-end encryption for data transfer and strong encryption for stored data** - **Implement real-time monitoring and intrusion detection systems** - **Conduct penetration testing and vulnerability assessments to identify and address security gaps**

Table 1. Five levers to operationalise the trust-building principle of 'security', with exemplary actions

However, in our view, these methods are not sufficiently comprehensive to assess the performance of trust building activities set in Table 1. A key limitation of surveys is their lack of continuous monitoring, as they are usually disseminated in long time intervals.

To complement survey data, we propose the introduction of trust performance indicators (TPI) (Gille et al. 2024; Gille et al. 2025a). TPIs are intended to bring the data collection method closer to the point of action and to facilitate routine data collection. At present, different research streams have developed evaluation frameworks in the digital health area, which can either complement TPIs or serve as context in which TPIs can be embedded. Examples include the "Design and Evaluation Framework for Digital Health Interventions" and the "Digital Public Health Maturity Matrix" (Kowatsch et al. 2019; Maaß 2024).

TPIs are a set of indicators that, in analogy to Key Performance Indicators or Quality Indicators, provide meaningful data about the performance of each trust-building action. When data output is high-frequency, there is an opportunity to act in time and adjust trust-building actions where needed. In this way, TPIs not only support the evaluation of trust-building efforts but also facilitate the continuous improvement of the digital health initiative itself (Gille et al. 2024).

Fourthly: Refine your actions

Trust-building is not a one-off action; it requires continuous engagement and adjustment. On the one hand, the evaluation of trust-building activities demands corrective measures where necessary. On the other hand, the underlying trust frameworks may evolve over time, especially in heterogeneous communities characterised by rapid digital transformation, the introduction of unfamiliar technologies and spillover effects from trust dynamics in unrelated initiatives beyond the healthcare sector. We advise a proactive approach on two fronts:

- continuous improvement of the initiative in response to internal evaluation; and
- adaptation of the initiative in response to evolving user perceptions of trustworthiness, which may manifest in changing conceptual frameworks.

Ways Forward

Building trustworthy digital health initiatives requires proactivity, leadership, resources, systems thinking and continuous action. We need to overcome the theory–practice gap and move beyond conceptual work describing trust, shifting the focus to concrete, operational steps. At present, we have a good understanding of what user trust is and the characteristics of trustworthy digital health initiatives. It is therefore time to act and confidently start building them.

While calls for action on trust are necessary, we must move beyond abstract debate and start delivering digital health solutions that users can experience – and that offer real, tangible benefits. If we fail to demonstrate these benefits and make such initiatives accessible and meaningful to user communities, we risk remaining locked in theoretical and ultimately unproductive debates about the importance of trust. Too often, we ask users to place their trust in the potential of digital health initiatives – offering promises rather than enabling them to experience concrete value in return.

> "We need to overcome the theory–practice gap and move beyond conceptual work describing trust."

A prominent example in many European countries are the endless attempts to introduce national electronic health systems (Papadopoulos et al. 2025). In Switzerland, for instance, it is hardly possible for professionals and the public to experience the benefits of a fully implemented national electronic health record system, as it is not operationalised in practice; only 0.8% of the population had activated their record as of 2024 (Bundesamt für Gesundheit 2024).

In everyday life, trust is typically built through repeated positive experiences with a technology or another entity. Normally, it remains a silent issue and only surfaces in public discussion when trust is declining or broken. With this insight in mind, our focus should shift away from abstract conversations about trust and towards actively building trustworthy initiatives that deliver clear benefits to the intended user community. A pragmatic, stepwise methodology – such as the four-stage approach proposed above – offers a manageable route through the complexity of large systems. Rather than be puzzled by theory, let us take the first of those four steps and begin operationalising trust in practice.

Conflict of Interest

Felix Gille works at the Federal Chancellery of Switzerland, the views expressed in this article are the views of Felix Gille and not of the Federal Chancellery.

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Own Your Data: Transforming Healthcare Through Data Ownership

The “Own Your Data” (OYD) framework empowers healthcare organisations to transform fragmented, underused data into a strategic asset. By aligning operations, governance and architecture, OYD improves efficiency, patient outcomes and innovation. A successful use case in Peru’s healthcare for the employees of the mining sector shows how OYD reduced delays, streamlined reporting and enabled proactive care, demonstrating its global relevance in modernising healthcare systems.

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key points

- OYD turns disorganised data into a strategic asset for healthcare organisations.
- The framework includes five clear pillars for data alignment and governance.
- It improves efficiency, accuracy and proactive care through structured transformation.
- A Peruvian case showed reduced delays and better health outcomes using OYD.
- OYD supports scalable, sustainable and people-centred data use across health systems.

In today’s data-driven world, the ability to manage and derive value from information is no longer a technical ambition—it is a strategic necessity. Nowhere is this more critical than in the healthcare sector, where lives depend on accurate, timely and accessible data. As healthcare systems grapple with increasing complexity, the “Own Your Data” (OYD) framework offers a structured pathway toward operational excellence, improved patient outcomes and predictive capabilities.

Rather than allowing data to remain fragmented, misunderstood or underused, OYD encourages organisations to reimagine how data is structured, governed and applied. The framework equips healthcare institutions to go beyond digitisation by fostering a genuine data-driven culture. When implemented effectively, it not only improves efficiency but also enables proactive, informed decision-making at all levels of care delivery.

Understanding the OYD Framework

The Own Your Data (OYD) framework is a comprehensive methodology for turning data into a strategic asset. It recognises that data on its own, without organisation, structure and purpose, is insufficient. OYD is designed to address systemic weaknesses in how organisations perceive and manage their information flows, offering a step-by-step approach that can be adapted across sectors, including healthcare.

The framework unfolds through five core pillars:

1. **Understanding and Translating Organisational Processes into Data Terms**
2. **Aligning the Data Model to Reflect Operational Realities**
3. **Establishing Governance Structures and Policies**
4. **Designing Scalable and Unified Data Architectures**
5. **Democratising Data Use and Driving Innovation**

This approach ensures that data is not only accurate and centralised but also meaningful and accessible to those who need it—clinicians, administrators, analysts and decision-makers.

The Critical Role of Data in Healthcare

Healthcare is increasingly data-dependent. From electronic health records (EHRs) to diagnostic imaging, from patient monitoring to public health reporting, the volume and variety of healthcare data are vast and growing. Yet, despite this abundance, many healthcare organisations struggle to harness its full potential.

Common issues include:

- **Fragmented information systems** that store patient data across multiple, incompatible platforms;
- **Lack of standardisation**, leading to conflicting definitions and interpretations of the same data;
- **Manual reporting processes** that consume valuable clinical and administrative time;
- **Poor data quality**, which undermines trust in information and delays decision-making.

In environments where every second matters, these issues create barriers not just to efficiency, but to safety and quality of care. OYD addresses these challenges by helping organisations rethink their data ecosystems, realign systems and processes, and cultivate a shared understanding of data's role in delivering better healthcare.

OYD in Practice: A Use Case in Peruvian Occupational Health

To understand how OYD can be applied in real-world healthcare settings, consider its implementation within occupational health services for mining workers in Peru. Mining is a high-risk sector with a significant impact on national employment and economic output. In 2024, approximately 240,000 people were employed in the

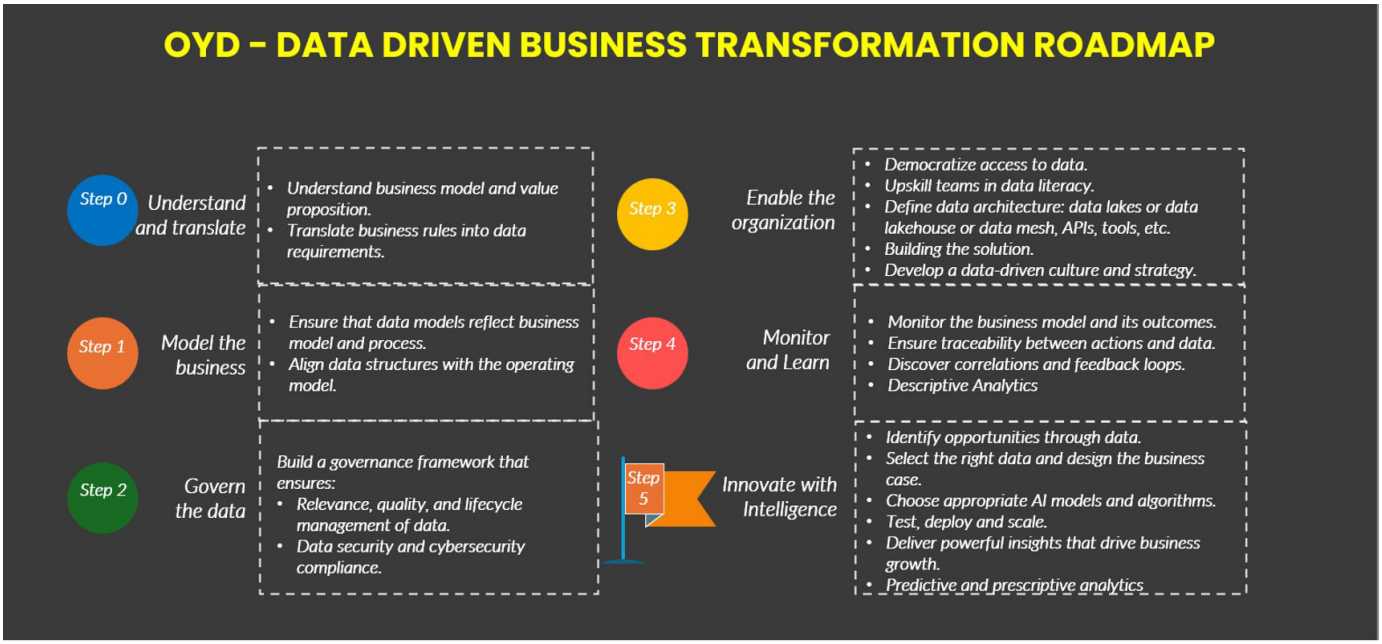

Figure 1. Business Transformation Roadmap Aligned with OYD Principles. Source: Ciclus Group

country's mining sector, many of them in physically demanding and hazardous roles.

Occupational health providers serving this population faced considerable operational challenges:

- Delays in processing medical examinations due to disconnected systems;
- Inconsistent and duplicated data across platforms;
- Manual report generation leading to extended working hours;
- Lack of a standardised approach to service pricing and clinical operations.

Phase 2: Aligning the Data Model to the Organisational Model

Once a shared understanding was achieved, attention shifted to the data model. This involved examining how well the structure of databases reflected actual business operations.

The analysis revealed:

- Missing entities in the data model—critical components that were invisible to the system;
- Redundant tables creating conflicts and undermining referential integrity.

> "The ability to manage and derive value from information is no longer a technical ambition—it is a strategic necessity."

This disorganised environment made it difficult to manage risk, respond quickly to emerging health issues or provide high-quality preventive care.

By applying the OYD framework, the healthcare provider undertook a structured transformation that addressed these core issues. The transformation was carried out in collaboration with Ciclus Group, a consultancy specialising in digital transformation, under the guidance of its CEO, Marita, who supported the structured implementation of the OYD framework.

Phase 1: Understanding and Translating Processes into Data Terms

The first step involved mapping the organisation's value proposition and operational processes. A multidisciplinary team analysed how data flowed across departments and identified disconnects between business expectations and technical implementations.

Key findings included:

- Varying interpretations of key terms and metrics across departments;
- Four separate IT systems with little interoperability;
- Gaps between clinical workflows and how data was captured.

These insights provided the foundation for realigning processes and data models around shared definitions and priorities.

Addressing these issues ensured that the data systems were capable of accurately representing and supporting the provider's core functions, such as patient intake, follow-up care and compliance reporting.

Phase 3: Establishing Data Governance

With structure in place, the next priority was governance—ensuring the consistency, security and usability of data across its lifecycle. A governance framework was introduced, covering:

- Data quality standards;
- Access control policies;
- Cybersecurity and regulatory compliance.

In parallel, a cultural change effort focused on improving data literacy within the workforce. Staff at all levels were trained not just in new tools, but in understanding the significance of data in their day-to-day work.

This combination of technical and cultural measures helped embed data governance as a shared organisational value, rather than a top-down mandate.

Phase 4: Designing a Unified Data Architecture

To eliminate fragmentation and streamline operations, a centralised data architecture was implemented. This included a data warehouse for structured operational reporting and a data lakehouse to handle larger, more diverse datasets.

Benefits included:

- Consolidated access to patient records and clinical history;

- Real-time generation of reports previously compiled manually;
- Simplified monitoring of health indicators across the workforce.

This architectural upgrade also laid the groundwork for scalability, allowing new functionalities and datasets to be incorporated without requiring a complete system overhaul.

Phase 5: Democratising Data Use and Enabling Innovation

The final phase focused on enabling healthcare teams to apply data insights in real time. Through internal training programmes, teams learned to access, interpret and act on the data available to them.

Examples of resulting innovations included:

- Early detection of health risks through data patterns in examination results;
- Alerts for follow-up appointments based on individual medical histories;
- Development of new clinical services based on observed needs and trends.

These improvements marked a shift from reactive care to proactive, personalised health management.

Results: Tangible and Strategic Benefits

The application of the OYD framework in this case led to measurable improvements:

- **Operational efficiency:** Automated systems reduced the time and effort needed for report generation and data processing;
- **Accuracy and integrity:** Standardised records helped eliminate duplications and conflicting information;
- **Improved patient outcomes:** Faster diagnostics and personalised alerts improved the quality of care;
- **Transparency:** Consistent data supported fair and predictable service pricing;
- **Strategic agility:** With reliable information, the provider could better forecast needs and allocate resources.

What emerged was not only a more functional information system but also a more agile and confident healthcare operation. By owning their data, the provider gained the clarity and control needed to support workers in a demanding, high-risk sector.

The Broader Implications for Healthcare

While the case in Peru is context-specific, the lessons are broadly applicable. Healthcare providers around the world face similar challenges: disjointed systems, data overload and limited ability to generate actionable insights.

> "With OYD, information becomes an enabler of strategic care, not a bottleneck."

The OYD framework offers a scalable solution to these issues. It is not dependent on specific technologies or vendor platforms but is instead a strategic methodology that can be adapted to different organisational contexts.

By investing in OYD, healthcare providers can:

- Enhance care quality through timely, accurate information;
- Streamline operations by eliminating manual, redundant tasks;
- Support regulatory compliance through well-governed data practices;
- Empower clinicians and staff to make evidence-based decisions.

Crucially, the cultural component of OYD ensures that improvements are sustainable. It's not just about systems—it's about people understanding, trusting and using the data at their fingertips.

Conclusion: From Data Chaos to Clarity

The Own Your Data framework is not simply a trend—it is a roadmap to modernising healthcare. In an increasingly digital world, the ability to manage and use data effectively will define the leaders of tomorrow's health systems.

The Peruvian use case demonstrates what is possible when healthcare organisations commit to structured, comprehensive data transformation. With OYD, information becomes an enabler of strategic care, not a bottleneck.

As healthcare continues to evolve under pressure from ageing populations, chronic diseases and rising costs, data must move from the periphery to the centre of operations. OYD offers a pathway to get there.

The question for healthcare leaders is no longer whether to embrace a data strategy, but how quickly they can implement one that empowers their teams, improves outcomes and sustains impact.

Conflict of Interest

None

Digital Advancements in Saudi Arabia's Health System: A Blueprint for Change?

Saudi Arabia's Vision 2030 marks one of the most ambitious national transformation strategies in recent global history. Launched in 2016 by Crown Prince Mohammed bin Salman, the agenda aims to diversify the economy, reduce dependency on oil and modernise public services, including healthcare. Despite political and cultural differences from Western democracies, Saudi Arabia's digital health advancements present a case study of rapid transformation, with structural, technological and strategic reforms of global relevance.

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key points

- Vision 2030 aims to modernise healthcare and boost life expectancy to 80 years.
- Non-communicable diseases drive a shift toward preventive healthcare strategies.
- The Seha Virtual Hospital leads in AI-driven remote care and telemedicine.
- Public-private partnerships are central to Saudi Arabia's health system reform.
- A unified health data platform integrates services across hospitals and pharmacies.

Vision 2030 and the Role of Health Sector Modernisation

At the heart of Vision 2030 is the belief that a healthy population is essential for a thriving economy. Healthcare has been designated a cross-cutting priority with clear national goals:

- increase life expectancy from 74 to 80 years,
- reduce traffic-related mortality,
- boost preventive care,
- and implement digital medical infrastructure (Vision 2030, 2016).

The initiative also seeks to align healthcare with international best practices by encouraging public-private partnerships and expanding medical education programmes.

The transformation of the healthcare system is not limited to infrastructure; it encompasses institutional reforms and governance innovations. Health objectives are closely linked with ministries of economy, education and technology to ensure that reforms are integrated rather than isolated (Health Sector Transformation Program 2023).

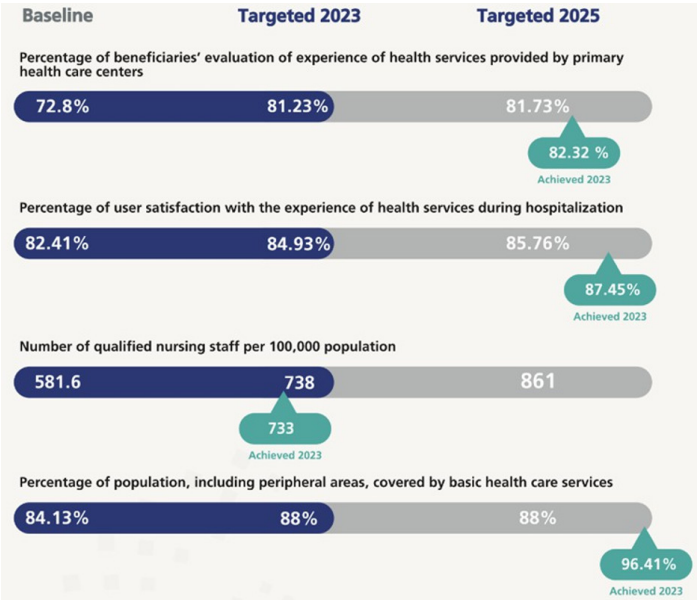

Figure 1: Health Sector Transformation Program: Key Performance Indicators (2023)

Demographic Pressures and Public Health Challenges

Saudi Arabia's population is both young and rapidly growing, with a median age in the early thirties and a steady annual growth rate. This demographic profile offers significant economic and healthcare planning advantages. The country is experiencing a demographic shift, with a steadily growing elderly population that is expected to place increased pressure on healthcare and social support systems in the coming decades.

More pressing is the surge in non-communicable diseases (NCDs). Currently, NCDs account for 73% of all deaths, and diabetes alone is expected to affect 7.5 million people by 2045 (World Bank 2021). These challenges necessitate a shift from reactive to preventive healthcare, a shift central to the Vision 2030 strategy (Health Sector Transformation Program 2023).

Current State of the Health System: Strengths and Gaps

Saudi Arabia operates a dual-sector healthcare system: over 60% of services are publicly provided, while the rest are delivered by private and military institutions (Saudi Ministry of Health, 2024). Healthcare is free for Saudi citizens and public-sector expatriates. Healthcare spending in the country is heavily concentrated on hospitals, while primary and preventive care remain underfunded, creating imbalances in service delivery. This imbalance results in overburdened tertiary centres and inadequate rural coverage.

To address these issues, the Health Sector Transformation Program (Fig. 1) was introduced. Its four core goals are: universal healthcare access, including in rural areas, enhanced patient satisfaction (target: 85.76%), stronger preventive programmes and early disease detection and reduction of traffic fatalities to 5 per 100,000 inhabitants (Health Sector Transformation Program 2023).

Digitalisation as the Backbone of Reform

The digital transformation of Saudi Arabia's health system is among the most comprehensive in the region. A cornerstone of this transformation is the National Platform for Health and Insurance Exchange Services (NPHIES). This platform integrates data from over 14 million insured citizens, 480 hospitals, 2,300 primary care centres and 8,700 pharmacies, making it one of the most extensive Health Information Exchanges (Saudi Ministry of Health, 2024).

> "The Seha Virtual Hospital […] has been recognised by the Guinness Book of World Records as the world's largest telemedicine network."

The flagship innovation is the Seha Virtual Hospital, which has been recognised by the Guinness Book of World Records as the world's largest telemedicine network. In 2023 alone, it conducted 480,000 consultations, many using AI-based diagnostics and robotic surgery (Saudi Press Agency 2022). The platform supports remote care, reducing dependency on urban hospitals and enabling access in underserved areas.

Structural Enablers of Digital Success

Saudi Arabia's digital health transformation is driven by a coordinated mix of structural reforms, policy innovation and targeted investments. Rather than isolated initiatives, these efforts are part of a larger national strategy aimed at modernising healthcare delivery and strengthening system resilience. Key focus areas include public-private collaboration, infrastructure development and a growing innovation ecosystem that positions the Kingdom at the forefront of digital health advancement.

- ***Public-Private Partnerships (PPP):*** By 2030, around 295 hospitals and 2,259 health centres will transition to PPP models, encouraging international technology transfer (Saudi Digital Government Authority, 2025).
- ***Infrastructure Investment:*** A significant share of the national budget is allocated to healthcare and social development with a $66 billion (about €56.5 billion) allocation being used to build 20,000 new beds, specialty clinics and research hubs, reflecting the government's commitment to sectoral modernisation and increased privatisation through public-private strategies (U.S. International Trade Administration, 2023).
- ***Research and Innovation Ecosystem:*** Saudi Arabia invests 2.5% of its GDP into R&D, focusing on biotechnology, pharma innovation and AI applications in health (Reuters, 2023).

Global Lessons and Transferability

Saudi Arabia's healthcare reforms exemplify a comprehensive, forward-looking approach to system transformation in the 21st century. Rather than following incremental change, the Kingdom has embraced leapfrogging by directly deploying technologies like telemedicine and artificial intelligence to modernise care delivery without reliance on legacy systems (Saudi Press Agency, 2022). Central to this success is the creation of a national Health Information Exchange (HIE), which has enabled the integration of fragmented data systems and improved coordination across hospitals, clinics and pharmacies (Saudi Ministry of Health, 2024).

In parallel, the government has fostered a supportive environment for international collaboration, encouraging major global technology companies to establish regional headquarters in exchange for market access, resulting in substantial investment in digital infrastructure and health innovation (Reuters, 2023). These changes were made possible by a cultural shift that prioritised public engagement, healthcare workforce training and cross-sector alignment of health priorities (Health Sector Transformation Program, 2023). Together, these strategies demonstrate how developing nations can leap ahead in health system modernisation by aligning policy, technology and global partnerships.

> "Saudi Arabia is pursuing a bold and consistent future strategy, where digitalisation is the foundation for everything."

Conclusion: Toward Future-Ready Healthcare

Saudi Arabia is pursuing a bold and consistent future strategy, where digitalisation is the foundation for everything. Its rapid changes are partly enabled by a specific national agenda. However, the principles behind its digital transformation, including long-term vision, cross-sector governance, measurable outcomes and public-private collaboration, are universally applicable.

In a world where healthcare systems face the dual pressures of rising costs and demographic shifts, Saudi Arabia offers a scalable, tech-driven blueprint. Countries seeking to future-proof their healthcare infrastructures should not only monitor but also meaningfully learn from Saudi Arabia's digital evolution and pragmatically adopt those factors that can drive the success of their healthcare.

Conflict of Interests

None

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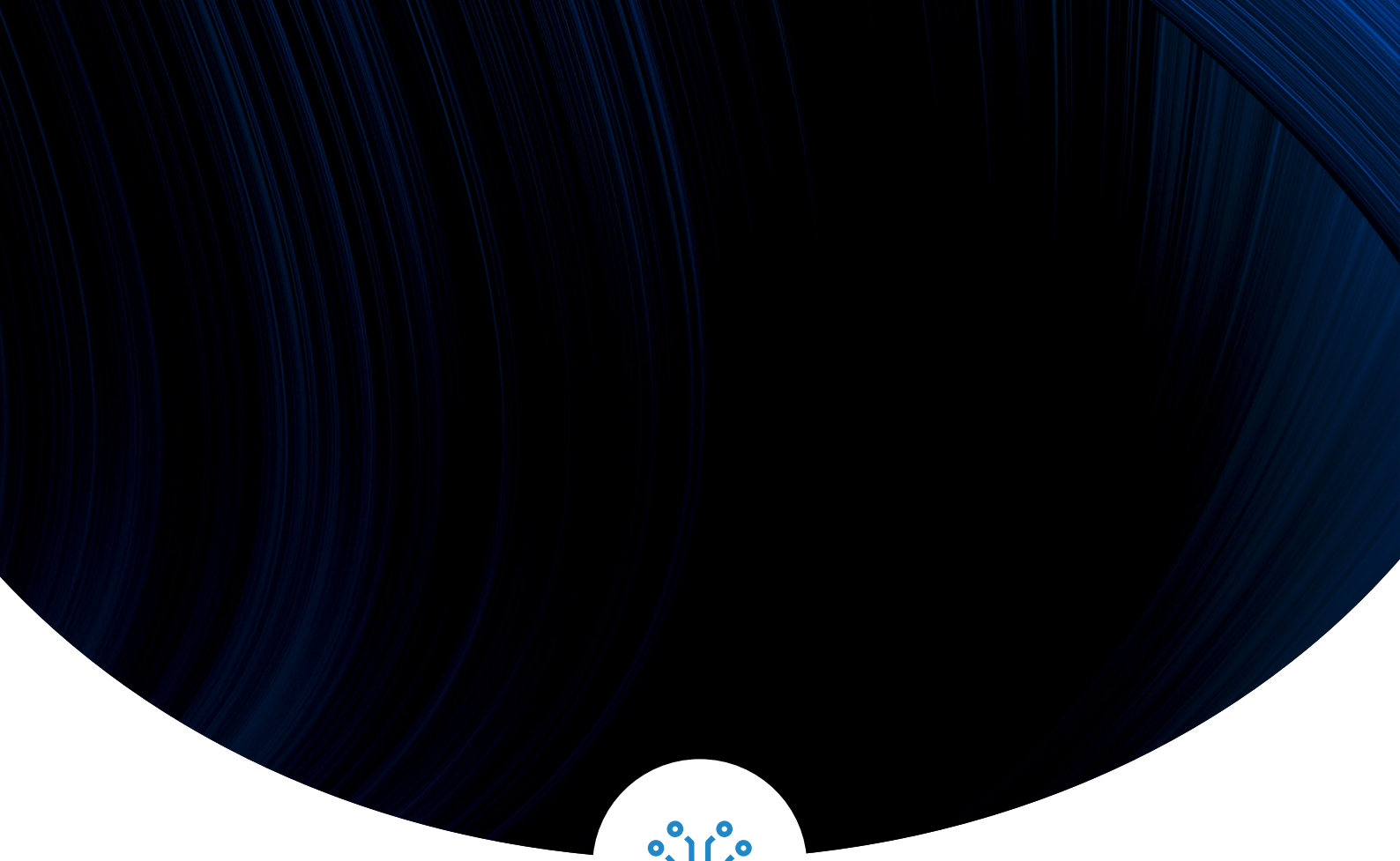

Women's Health

Improving Maternal and Neonatal Outcomes with 3D-Printed Foetoscopes in Kenya

Hourly foetal heart monitoring with individualised 3D-printed fetoscopes in a Kenyan maternity ward improved detection of non-reassuring foetal status, reduced emergency caesarean sections, prevented perinatal deaths and raised satisfaction for mothers and staff. The innovation showed that local 3D printing can deliver low-cost, rapid solutions to equipment shortages, strengthen infection control and enhance health system resilience in resource-limited settings.

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key points

- Individualised 3D-printed fetoscopes enabled hourly foetal heart monitoring.
- Earlier detection of non-reassuring foetal status reduced emergency caesarean sections.
- No foetal deaths occurred in the group with personalised 3D-printed fetoscopes.
- Maternal and staff satisfaction increased with improved monitoring and outcomes.
- Local 3D printing provided low-cost, rapid solutions to equipment shortages.

Introduction

Caesarean section is a vital surgical procedure used to deliver a baby when a life-threatening condition arises during labour or pregnancy for either the mother or the foetus. According to the World Health Organization, it is often indicated in cases of non-reassuring foetal status, placental abruption or severe pre-eclampsia. It is classified by the American College of Obstetricians and Gynaecologists and the National Institute for Health and Care Excellence as a Category I or II intervention, meaning that delivery should occur within 75 minutes of the decision to operate in order to optimise outcomes.

Over the past four decades, the use of caesarean section has risen steadily across the world. Global prevalence increased from 7% in 1990 to 21% in 2018, with projections suggesting that it could reach 28.5% by 2030. While caesarean section can be life-saving when medically indicated, particularly in the presence of non-reassuring foetal status, cephalopelvic disproportion, malpresentation, hypertensive disorders of pregnancy, prolonged labour, macrosomia or multiple gestation, its rising use is cause for concern. The World Health Organization stated as early as 1985 that there was no justification for any region to have rates higher than 10–15%. Beyond this threshold, increasing numbers of procedures do not bring additional benefits but may instead expose women to greater risks, including higher morbidity and mortality, as well as placing further strain on already limited health resources.

The risks are particularly evident in low- and middle-income countries. In Africa, the average caesarean rate has been reported at 9%, ranging between 0.6% and 18% depending on region and facility type. In Kenya, the national rate is estimated at 14.4%, with the majority performed as emergency operations. A study of 321 Kenyan women undergoing caesarean section found that 89.4% of procedures were emergencies, most commonly for non-reassuring foetal status, prolonged labour or a history of previous caesarean section. Public health facilities tend to report higher

emergency rates than private institutions, and the rising use of the procedure across the country has raised significant concerns for maternal and neonatal health.

Non-reassuring foetal status, formerly known as foetal distress, remains a critical determinant of emergency intervention. It is a term used to indicate oxygen deprivation in the foetus, whether temporary or permanent, which can progress to hypoxia and metabolic acidosis. Globally, it affects between 8.9% and 30.7% of pregnancies and is one of the major contributors to stillbirth and early neonatal death. In low- and middle-income countries, where access to timely obstetric care may be limited, the burden is especially severe. Non-reassuring foetal status is also a risk factor for long-term complications such as cerebral palsy.

A number of maternal and obstetric factors contribute to non-reassuring foetal status. These include antepartum haemorrhage, intrauterine growth restriction, amniotic fluid disorders and maternal illnesses. Obstetric interventions can also play a role, with induction or augmentation of labour, use of anaesthesia and the presence of meconium-stained amniotic fluid all associated with increased risk. Tocolytic treatment for preterm labour, particularly when frequent, may further contribute. The most common tool available for assessing foetal wellbeing in labour is foetal heart rate monitoring, either by intermittent auscultation or continuous electronic methods. In many low-resource settings, however, access is limited and intermittent auscultation with a shared foetoscope remains the standard.

Innovation in 3D Printing

Three-dimensional printing, also referred to as additive manufacturing, is a technique that creates physical objects layer by layer based on a digital model file. Unlike traditional manufacturing, which relies on moulds or extensive material removal, 3D printing uses less raw material and allows precise customisation. Once regarded as little more than an ambitious vision, it has become a tangible reality across many areas of healthcare. Today, 3D printing represents a significant opportunity to support pharmaceutical development, enable rapid production of implants and change the way doctors and surgeons prepare for procedures. It allows for personalised devices, faster turnaround and the capacity to innovate locally.

In many hospitals in low- and middle-income countries, such advances remain far removed from daily practice. Basic but essential tools can be in short supply. In Kenyan maternity wards, for example, once a mother is admitted to labour, monitoring of the foetus is done through intermittent auscultation using a foetoscope. For low-risk pregnancies, checks are usually performed every three hours and recorded on the partograph. In many public hospitals, a single foetoscope may be shared between all the women on the ward. Until the COVID-19 pandemic, infection prevention was not a major concern with this practice, but as awareness increased, the sharing of devices was recognised as a potential risk.

> "No foetal deaths were reported in the case group."

This necessity triggered an idea: to individualise foetoscopes, ensuring each mother had her own device at the bedside. The approach would not only reduce the infection risks associated with sharing, but also provide an opportunity to explore whether more frequent monitoring could improve detection of non-reassuring foetal status and reduce the need for emergency caesarean section.

Through a collaboration with the Pennsylvania University School of Engineering, a prototype 3D printer was donated to Uzima University School of Medicine. Using this machine, 32 foetoscopes were fabricated, enough to equip each bed in the maternity ward of Jaramogi Oginga Odinga Teaching and Referral Hospital. The devices were produced within 48 hours, a stark contrast to the lengthy procurement cycles that often characterise equipment supply in public health systems. This intervention represented not only an advance in infection prevention but also a test of how digital fabrication could alter clinical practice in a resource-constrained environment.

Methods

The study was designed as a case-control comparison in order to assess the impact of individualised 3D-printed foetoscopes on foetal heart rate monitoring, identification of non-reassuring foetal status and subsequent maternal and neonatal outcomes.

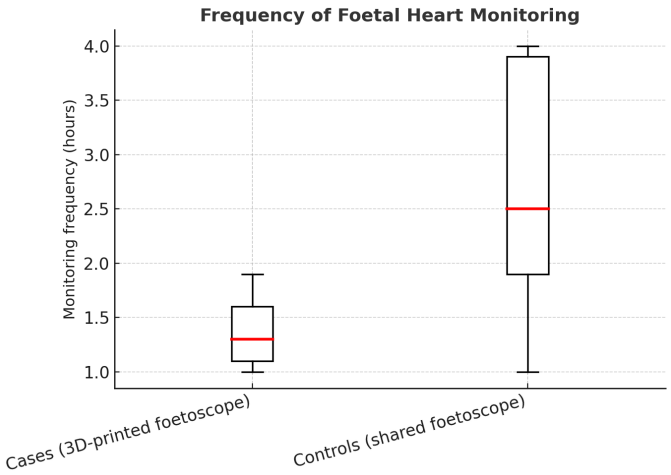

Figure 1: Frequency of foetal heart monitoring (hours) in cases and controls

The prospective case group included 32 mothers admitted to the maternity ward at Jaramogi Oginga Odinga Teaching and Referral Hospital. Each mother was allocated a personalised 3D-printed foetoscope at the bedside, and foetal heart monitoring was conducted hourly throughout labour. Their outcomes were compared with a retrospective control group of 32 mothers, selected randomly from delivery records covering the preceding six months, when only one foetoscope had been available for the entire ward and monitoring was carried out every three hours.

Medical records for both groups were reviewed until the time of discharge following delivery. Data collected included the frequency of foetal examinations, time from admission to detection of non-reassuring foetal status, interventions undertaken, decision-making intervals and maternal and neonatal outcomes.

In addition to clinical data, qualitative information was obtained through interviews with maternity nurses and attending doctors who had been working in the unit during both study periods. They were asked about their experiences before and after the 3D printing intervention, with particular focus on workflow, timeliness of interventions and perceptions of outcomes. This input provided valuable insights into staff perspectives and the practical feasibility of implementing individualised monitoring.

Statistical analysis involved summarising categorical variables with frequency counts and percentages, while continuous variables were described using medians and interquartile ranges. Associations between categorical variables and outcomes were assessed with Pearson's chi-square or Fisher's exact tests, as appropriate. For continuous variables, non-parametric Wilcoxon–Mann–Whitney tests were used. The normal foetal heart rate during labour, against which changes were assessed, was defined as 110–160 beats per minute.

Whenever hourly monitoring revealed abnormalities—such as rates above the upper threshold, below the lower threshold, or irregular, muffled or unusually high-volume heart sounds—medical interventions were applied immediately according to the identified cause. These included addressing maternal conditions, pregnancy complications or umbilical cord and placental issues. Only when prompt medical management failed to normalise the situation were mothers taken for emergency caesarean section.

Results

The introduction of individualised 3D-printed foetoscopes in the maternity ward led to clear differences in both monitoring practices and clinical outcomes when compared with the period in which a single shared foetoscope had been used.

With the personalised approach, the frequency of foetal heart rate monitoring increased significantly. Mothers with their own bedside foetoscope were checked on average every 1.3 hours (interquartile range 1.1–1.6), whereas those in the control group with a shared device were checked approximately every 2.5 hours (IQR 1.9–3.9). The difference was highly significant ($p < 0.001$).

Earlier detection of non-reassuring foetal status was a direct consequence of the increased monitoring frequency. Among mothers with individualised foetoscopes, abnormalities were identified within a

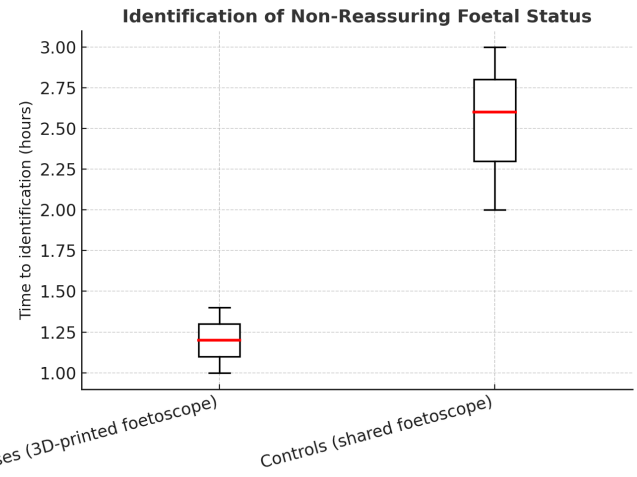

Figure 2: Time to identification of non-reassuring foetal status (hours) in cases and controls

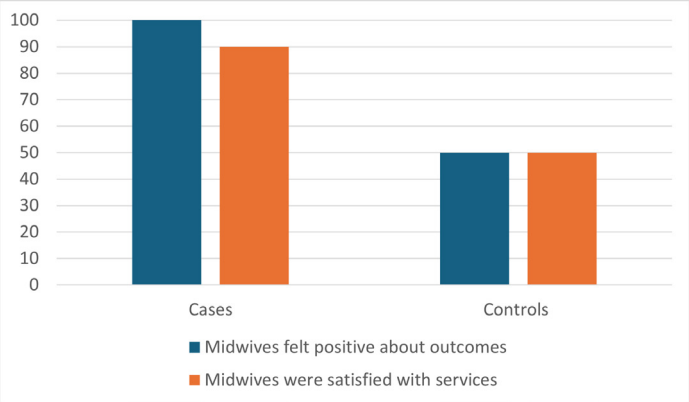

Figure 3: Midwives' satisfaction with services and outcomes (each mother with a 3D foetoscope versus shared device)

median of 1.2 hours (IQR 1.1–1.3), compared with 2.6 hours (IQR 2.3–2.8) in the control group ($p < 0.001$). The shorter interval allowed for more rapid intervention, often avoiding progression to severe foetal compromise.

This translated into improved maternal and neonatal outcomes. The proportion of mothers requiring emergency caesarean section to save the foetus was lower in the group with individualised foetoscopes, at 13%, compared with 38% among those sharing a device ($p = 0.021$). Furthermore, no foetal deaths were reported in the case group, while three deaths occurred in the control group, representing 9.4% of cases, although this difference did not reach statistical significance ($p = 0.240$).

perinatal deaths and enhance both maternal and staff experience within the maternity unit.

Discussion

The findings from the maternity unit demonstrate that relatively simple and inexpensive technological innovations can make a significant difference to clinical outcomes in low-resource environments. The provision of individualised 3D-printed foetoscopes allowed for more frequent monitoring, leading to earlier detection of non-reassuring foetal status and reducing the need for emergency caesarean section. This change not only improved outcomes for mothers and newborns but also enhanced the working environment for staff.

From a clinical perspective, the link between more frequent monitoring and reduced emergency interventions is clear. By identifying abnormal foetal heart rate patterns more quickly, staff were able to intervene medically to stabilise the foetus, whether by addressing maternal conditions, managing pregnancy complications, or responding to umbilical cord and placental factors. Only when such interventions were unsuccessful did mothers require surgical delivery. This explains the reduction in emergency caesarean sections and the absence of foetal deaths among mothers monitored with their own foetoscopes. The decline in perinatal deaths also reflects the benefits of earlier recognition and timely action.

> "Midwives noted that earlier detection of foetal compromise (…) contributed to a sense of professional fulfilment."

Maternal satisfaction with care was also markedly higher when each mother had her own foetoscope. In the case group, 94% expressed satisfaction, compared with 63% in the control group ($p = 0.002$). Staff satisfaction was also reported to be higher. Midwives noted that earlier detection of foetal compromise, prompt interventions and better outcomes for both mothers and babies contributed to a sense of professional fulfilment.

The overall effect of introducing 3D-printed foetoscopes was therefore to reduce delays in monitoring, allow earlier identification of non-reassuring foetal status, decrease the proportion of emergency caesarean sections, prevent some

The broader implications extend to health systems and hospital management. One of the most striking observations was the difference in cost and accessibility between traditional procurement and local 3D printing. The printer produced 32 foetoscopes within 48 hours, compared with a single shared foetoscope that had been in use for the preceding year despite repeated requisition requests. The cost of producing each device with 3D printing was only a fraction of the price of purchasing a new one from commercial suppliers. This capacity to fabricate essential equipment rapidly and affordably has obvious value in health systems where resources are constrained and supply chains are unreliable.

Beyond cost savings, the intervention also revealed important social and professional dimensions. Mothers expressed greater satisfaction with the care they received, linked both to more attentive monitoring and to better outcomes. Midwives and doctors reported increased satisfaction and morale, as they were able to deliver more babies safely and reduce the stress associated with emergency interventions and poor outcomes. An unexpected finding was the enthusiasm among staff for further use of the 3D printer. Requests were made for the technology to be available for routine use, including the fabrication of spare parts for incubators and other hospital equipment, as well as the production of additional basic tools. This interest highlights how frontline staff recognise the potential of digital fabrication to improve their work environment and service delivery.

It is also worth noting that the reduction in emergency caesarean sections has broader implications for maternal health. Caesarean delivery, while often life-saving, is associated with higher risks of morbidity and mortality compared with vaginal birth. According to data from the American College of Obstetricians and Gynaecologists, caesarean delivery carries a maternal mortality rate of 35.9 per 100,000 live births, compared with 9.2 for vaginal delivery. Reducing unnecessary or avoidable caesarean sections is therefore important not only for short-term outcomes but also for long-term maternal health and the sustainability of health systems.

Finally, the experience at Jaramogi Oginga Odinga Teaching and Referral Hospital highlights how technological innovation can support professional pride and motivation. Midwives reported higher levels of satisfaction in their work, not only because outcomes were better, but because they could see almost all of their patients leaving the hospital with healthy babies after normal deliveries. Such morale-boosting effects are valuable in healthcare environments where staff often face heavy workloads and limited resources.

"Mothers expressed greater satisfaction with the care they received, linked both to more attentive monitoring and to better outcomes."

The role of 3D printing should also be considered in the wider context of digital health and innovation. In many developing countries, budgets are limited and healthcare competes with other pressing needs for scarce resources. As a result, even simple items such as foetoscopes may not be purchased in adequate numbers. Digital fabrication provides a way to overcome these structural barriers, enabling hospitals to produce what they need in-house and to respond quickly when shortages or breakdowns occur. The experience of using 3D printing for foetoscopes in this maternity unit therefore offers a proof of concept that could be extended to many other areas.

The original study also touched on the potential contribution of artificial intelligence, particularly in developing applications to solve medical problems where laboratory support is not available. While AI was not part of the intervention itself, it is relevant to note that Africa has a high level of smartphone ownership, especially among medical personnel. The combination of accessible AI applications with 3D printing could in future enhance diagnosis, treatment planning and the rapid production of necessary equipment. Although this remains aspirational, it underlines the need to consider digital technologies in an integrated manner.

Limitations

While the findings of this study are promising, several limitations must be acknowledged. The relatively small sample size means that the results cannot be generalised without caution. A larger cohort would provide greater statistical power and more confidence in the observed differences.

There is also the possibility of confounding factors that were not controlled for. The timing of cases and controls may have influenced outcomes. Mothers in the case group may have presented directly to Jaramogi Oginga Odinga Teaching and Referral Hospital, whereas mothers in the control group may have been referred after prolonged or non-progressing labours in other facilities. This referral bias could have contributed to higher complication rates among controls.

In addition, while the case group largely included mothers with non-reassuring foetal status as the main indication for caesarean section, the control group

may have had other indications, such as breech presentation or cord complications. The presence of multiple indications could have influenced both surgical decisions and outcomes. Neither group was assessed systematically for maternal co-morbidities or foetal conditions, which may also have affected results.

Practical difficulties were encountered during the study. One mother carrying triplets posed challenges for monitoring and interpretation, as it was not always possible to track all foetal heart rates accurately. This made decisions about interventions more complex, and outcomes were not straightforward to classify.

Another limitation relates to the scope of 3D printing itself. The study was limited to producing simple devices such as foetoscopes, but more complex anatomical models were not feasible with the materials available. For example, flexible models of the heart could have provided additional learning opportunities for staff, demonstrating how normal and abnormal heartbeats differ. Although advances in printing materials are closing the gap between reproduced anatomy and real soft tissue, this was not accessible within the study context.

Finally, the study did not attempt to explore the long-term sustainability of 3D printing in the hospital environment. While the devices were produced quickly and cheaply with the donated prototype, questions remain about maintenance, supply of materials and integration into routine hospital operations. Further work is needed to assess how such innovations can be embedded into health systems for lasting benefit.

Conclusion and Recommendations

The experience at Jaramogi Oginga Odinga Teaching and Referral Hospital demonstrated that 3D printing can make a meaningful contribution to maternal and neonatal health in a resource-limited environment. By providing each mother in labour with a personalised foetoscope and enabling hourly monitoring, the intervention improved detection of non-reassuring foetak status, reduced the number of emergency caesarean sections, prevented some perinatal deaths and increased satisfaction for both mothers and healthcare staff.

The wider significance lies in showing that advanced digital technologies need not be restricted to high-income settings. With a single prototype 3D printer, a hospital was able to produce 32 foetoscopes in two days, replacing reliance on a single shared device. The cost of each printed foetoscope was far below the price of procuring equipment through conventional channels, and the immediate availability allowed rapid transformation of practice. In addition to the clinical benefits, the intervention fostered greater confidence and morale among midwives and doctors, who expressed enthusiasm for extending the use of the printer to produce spare parts and other equipment essential for daily service delivery.

For low- and middle-income countries, the implications are clear. Investment in computing and 3D printing offers a practical and cost-effective way to address equipment shortages, overcome procurement delays and strengthen service provision. Hospitals that embrace such technologies can manufacture basic tools, repair equipment and respond quickly to emerging needs. The capacity to innovate locally enhances resilience and reduces dependence on fragile supply chains.

The study also points towards future opportunities. While this intervention was limited to foetoscopes, 3D printing is already being used in other fields to produce implants, prostheses, surgical instruments and training models. With further development, hospitals could integrate digital fabrication into a wide range of clinical and non-clinical departments. In combination with other digital technologies such as artificial intelligence, the potential to transform service delivery is considerable. On the basis of these findings, it is recommended that health institutions in low- and middle-income countries invest in computing and 3D printing technology, both for training and for clinical service delivery. Hospitals should consider establishing in-house 3D printing facilities to ensure rapid access to essential tools and parts. Non-medical departments could also benefit from testing the technology for their own needs, further embedding digital fabrication into organisational practice.

The twinning of computing with medicine and surgery has the potential to deliver transformational solutions. By embracing 3D printing, healthcare facilities can provide more comprehensive and lifesaving services, making a tangible difference to maternal and neonatal outcomes and strengthening the resilience of health systems in the developing world.

Conflict of Interest

None.

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Training for Antimicrobial Resistance to Transform Health Services

Embedding antimicrobial resistance management in routine care demands cross-disciplinary skills, change management and interoperable IT. GDPR and legacy systems hinder integration of point-of-care tools such as RaDAR. Progress relies on shifting from silos to process-based teams and sustaining training with leadership support. Priorities include stepwise, evidence-backed adoption and a 2030 vision built on EU data spaces for early detection and cross-sector stewardship.

PROF. MADDALENA ILLARIO

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key points

- Cross-disciplinary skills are essential for AMR in routine care.
- GDPR and legacy IT block real-time integration of point-of-care tools.
- Hospitals must shift from silos to process-based teams.
- Ongoing training needs leadership support and change management.
- Adoption should be stepwise and evidence-based, in line with EU data spaces.

Maddalena Illario, Endocrinologist and Associate Professor at Federico II University of Naples, coordinates the Campania Reference Site of the European Innovation Partnership on Active and Healthy Living. A former coordinator of Campania's Health Innovation Division, she is chair of the Reference Site Collaborative Network and contributes to cross-disciplinary training on antimicrobial resistance.

During a 2025 EHTEL Imagining 2029 work programme session, *"The Digital Transformation Journey: Creating a digitally confident health and care workforce,"* Illario shared insights on how the hospital is preparing a future-ready workforce, including experience from the **RaDAR project.** Staff are focusing on leadership, point-of-care teamwork, collaboration and digital development (EHTEL 2025a). She also offered complementary insights into lessons learned on digital transformation at the EHTEL 2024 Symposium (EHTEL 2024a, b). Both sessions were supported by the Erasmus+ BeWell project (EHTEL 2025b).

Lessons from AMR Training

Q. What were the most significant lessons learned from implementing cross-disciplinary AMR training? How can these findings be scaled?

A. Cross-disciplinary training involves the challenge of engaging a variety of health and care (and other) professionals. While all the staff have hands-on experience in daily practice, they need to handle a different part of the patient journey when a case of AMR emerges.

Viewing AMR management as a process of interconnected activities facilitates reciprocal awareness of roles and responsibilities. At the same time, it sharpens the focus on specific elements of training topics and skills.

For scaling AMR training, similar interactive training sessions should be tailored to the specific needs, protocols and resources of each hospital or clinic. This includes adjusting content to reflect local infection control procedures, staff roles and IT infrastructure.

Q. What have been the main barriers and enablers in integrating point-of-care technologies, such as RaDAR, into routine hospital workflows?

A. Hospital workflows are supported by systems that are almost not interoperable with new modules, although, in theory, some improvements are foreseen in supplier contracts. This lack of interoperability locks in the entire hospital IT architecture, making it unfriendly to innovation, resistant to change and unable to take advantage of new tools that might otherwise be accessible, especially in university hospitals that integrate research, training and service provision.

The silos created by different scientific disciplinary sectors further hinder interdisciplinary results that could improve service processes, system sustainability and health outcomes.

To accelerate transformation, there is a need for top-down activation that changes how performance is assessed and incentives are applied across the whole process. It is important to account for service processes that still acknowledge different scientific and professional roles, but workflows must be reorganised to strengthen horizontal activities across the hospital.

> "Cross-disciplinary training involves the challenge of engaging a variety of health and care (and other) professionals."

Key barriers included the inability to integrate RaDAR in real time with health information systems due to hospital IT upgrades.

The **General Data Protection Regulation (GDPR)** restricts the hospital's ability to test new platforms, as hospital data cannot be moved outside the information system. This lack of data mobility worsens the innovation scenario and makes integration with new modules, platforms and tools difficult.

The main enablers for integrating RaDAR into routine workflows included a structured change-management plan, effective training, strong stakeholder engagement and successful technical installation.

Q. You mentioned a persistent gap between research outcomes and real-world service provision. What practical strategies have helped to close this gap in your work, and what still needs to be addressed?

A. We have applied several practical strategies and still face some outstanding challenges.

Engagement of all stakeholders involved in the process, regardless of their roles and levels, has helped identify pain points and untapped resources that could accelerate transformation, such as human resources and calls for funding. Co-creation of training, involving all stakeholders in a peer-to-peer approach to knowledge exchange, has also been stimulating for the hospital team.

> "Hospital workflows are supported by systems that are almost not interoperable with new modules."

From Research to Sustained Practice

Q. You describe a shift from a functional to a process-oriented hospital structure. What organisational adaptations were most critical in enabling this transformation?

A. The shift from functional to process is a major change and will take time. Resistance is driven by organisational culture built around professional roles rather than team building and value-added improvements.

Weak engagement of top management remains to be addressed, as there is still no clear prioritisation at policy level of the efforts needed to integrate innovation, or of the innovations available and their impacts. The constant focus on short-term priorities linked to political timeframes and associated appointments to top management roles negatively influences the medium- to long-term planning needed to ensure exploitation, sustainability and full impact. Strengthening the planning role of permanent

middle-management positions may help ensure continuity of relevant activities during political shifts.

Q. How do you ensure that training in digital tools is not just a one-off event but leads to sustained changes in clinical decision-making and interprofessional collaboration?

A. The ability to ensure medium- and long-term planning for training and innovation, in a way that is flexible and up to date, mitigates resistance to change. It strengthens confidence in digital solutions and technological innovations, especially when nurtured in a collaborative, team-based approach. This approach also helps build a sense of purpose and belonging that benefits productivity and service quality.

Building the AMR Ecosystem for 2030

Q. What are your priorities for making innovations in AMR management sustainable, both financially and operationally, within regional and national health systems?

A. Our influence on regional and national health systems may be limited. We can, however, ensure that our efforts generate evidence that the tested innovations are effective. The system can then be implemented stepwise, supported by customised training. Disseminating results to other interested networks and communities, such as the **EU Health Policy Platform (HPP)** and the **Transforming Health and Care Systems (THCS) Partnership**, is well within our reach.

Q. What would a fully digital, integrated and resilient AMR management ecosystem look like in 2030?

A. Such an ecosystem would build on the **common European open data space** to ensure that data can follow citizens. This would strengthen AMR monitoring and enable stewardship adapted to the local AMR profile. It would also support early detection of AMR through point-of-care testing to prevent further transmission across microbes. Integrated point-of-care testing would help monitor hotspots for AMR, such as hospitals, nursing homes and prisons.

> "Such an ecosystem would build on the common European open data space to ensure that data can follow citizens."

The European data space would also support data sharing across health, agriculture, and veterinary sectors to enable coherent and complementary policies and actions.

Conflict of interest

None.

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Hospital as a Service, not a Building (NHS 2025): Reflections on the Future

The NHS 2025 vision reimagines hospitals as decentralised, digital services focused on prevention and remote care. It prioritises integrated care pathways, interoperable records and national platforms for communication. Virtual hospitals and AI-enabled triage are proposed, yet artificial intelligence remains underutilised. Strategic investment in AI, ethical standards and workforce training is essential to deliver sustainable, patient-centred healthcare across evolving systems.

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key points

- Hospitals should be redefined as flexible, digital services rather than physical locations.
- Care pathways must prioritise virtual-first models for chronic and frail patients.
- Unified health records and secure clinician platforms ensure effective communication.
- Virtual hospitals and remote wards need structured funding and trained professionals.
- AI should be a core element in diagnosis, triage, monitoring and operational planning.

The document *"Hospital as a service, not a building"* (NHS 2025) proposes a deep reform of the British hospital system, steering it towards a more flexible, digital and patient-centred model. Here is a summary of its key recommendations, organised around strategic principles.

Principle 1: Reimagining Care Pathways

The report calls for a comprehensive clinical review of care circuits for patients with multimorbidity and frailty, led by specialists within an integrated system spanning primary, hospital and social care. A critical analysis of in-person versus flexible services is encouraged to redesign care pathways with a virtual-first approach where appropriate. These redesigned pathways should be assessed and improved through peer review programmes focused on care journeys rather than individual professionals or institutions.

To support implementation, local "SWAT teams" at ICS level should assist physicians and hospitals. Primary care "Pay by Results" (PbR) pilots are proposed, with tariffs adjusted to case complexity and administrative support provided by hospitals. The model is to be formally evaluated after three years to determine its scalability or potential replacement.

Principle 2: Prioritising Communication over Location

A national clinician-to-clinician communication platform, secure and tailored to NHS needs, is proposed. This would be complemented by a national professional directory integrated with AI-powered semantic search and supported by financial incentives to reward efficiency in clinical communication.

The report recommends the implementation of a mandatory Unified Care Record (UCR) across all health and social care providers, ensuring full interoperability. This should be supported by national standards for coding, interoperability, data quality and security.

Such a transformation is both ambitious and necessary, as the current hospital system is increasingly unfit for the needs of an ageing population, a rising burden of chronic disease and evolving public expectations. Detaching the concept of "hospital" from its physical location and redefining it as a network of integrated, digital services appears both disruptive and timely, especially following the COVID-19 pandemic.

> "Detaching the concept of 'hospital' from its physical location and redefining it as a network of integrated, digital services appears both disruptive and timely."

Legislation would enforce these standards, with a defined technical transition period. Local UCR pilots should precede national rollout, and electronic patient record (EPR) contracts should be limited to five years to promote competition, innovation and quality.

Principle 3: Redefining the Hospital Around Remote Care

The report advocates for "Remote General Hospital" pilots in at least three regions, with two-year evaluations covering costs, outcomes and user experience. It proposes defining a minimum set of mandatory services suitable for remote delivery, including virtual A&E and relevant specialties. Professional training should be adapted to these remote settings, in partnership with medical colleges.

Five-year guaranteed funding for virtual wards is recommended, with incentives for meeting care goals without increasing physical bed numbers. Nursing homes should be integrated into virtual wards through per-patient payments. Successful implementation requires dedicated personnel and a national repository of best practices and lessons learned. Data standards for remote monitoring should be established to ensure interoperability between devices and electronic records.

Critical Reflection on the "Hospital as a Service" Model

The report proposes transforming the hospital from a physical infrastructure into a distributed, digital and flexible service focused on prevention. This vision includes broad use of telemedicine, remote monitoring and unified health records, alongside the deployment of virtual hospitals and remote consultations. Structural reforms in funding, governance, interoperability and professional training are also central to the model.

The report clearly identifies key structural issues in the NHS, such as fragmentation, institutional rigidity and limited technological adoption. However, some aspects deserve further scrutiny, particularly the underappreciated role of artificial intelligence (AI), which is only superficially mentioned.

Critical Issues and Missed Opportunities

- **Underestimation of Artificial Intelligence:** While AI is briefly mentioned in connection with the clinical directory's semantic search, its broader potential as a driving force behind the new hospital model is not explored.
- **Implicit Distrust in Clinical Automation:** The report omits any reference to established AI applications such as assisted diagnosis, prediction of clinical deterioration, risk analysis or prioritisation of waiting lists—even though these technologies are already proving valuable in various health systems.
- **Absence of Ethical or Regulatory AI Strategy:** There is no discussion of how to address key concerns such as trust, explainability and medical oversight in an increasingly algorithm-driven healthcare environment.

Highlighting the Role of AI in the Hospital of the Future

Artificial intelligence should be positioned as a structural component of healthcare as a service. In **diagnosis and triage**, AI can enhance early detection of chronic, oncological or cardiovascular diseases, and support automated triage in virtual A&E settings.

For **monitoring and prediction**, algorithms can detect clinical deterioration in patients with conditions such as COPD, heart failure or diabetes, and reduce hospital readmissions through proactive alerts in virtual wards.

require a national deployment plan for clinical AI, the establishment of clear ethical and regulatory standards, and investment in digital talent and AI literacy among healthcare professionals.

> "Since implementation, more than 580,000 studies have been processed, with daily averages of around 5,700."

Clinical decision support systems can help physicians choose appropriate treatments based on historical data, scientific evidence and personalised risk-benefit assessments. **Operational optimisation** can also benefit from AI in managing waiting lists, bed occupancy, staff scheduling and demand forecasting based on seasonality, disease outbreaks or social determinants.

Final Recommendation

To build a truly innovative and sustainable "hospital as a service," artificial intelligence must be considered a strategic pillar, not a secondary tool. This will

These reflections go beyond the NHS report. Health systems everywhere should strategically embrace AI as a catalyst for the future of care.

Conflict of interest

None.

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Finance

Private Equity in Context for Independent Practices

Independent physician groups face mounting pressure from workforce shortages, rising costs, reimbursement cuts, tech demands and consumer expectations. Private equity is one of several partnership options alongside hospital or insurer alignment. While benefits can include operational efficiency and clinical control within agreed governance, careful partner selection and deal structuring is critical to ensure long-term physician alignment, cultural preservation and continued autonomy.

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key points

- Physician shortages and high nurse turnover strain independent practices.
- Rising labour and operational costs erode already thin profit margins.
- Reimbursement cuts further reduce revenue for smaller provider groups.
- Tech demands and consumer expectations add pressure on limited resources.
- Private equity can offer capital and scale but requires careful partner selection and deal structuring.

As the healthcare landscape evolves, five major macro trends are converging to challenge independent physician practices, compounding cost pressures, technological demands and shifting patient expectations into a perfect storm:

Persistent Physician Shortages and Workforce Shifts. Independent physician practices are facing a mounting crisis: a wave of retirements and insufficient replacement rates. Many long-standing physicians, accustomed to higher compensation and a slower pace during the COVID years, are opting for early retirement, thinning the ranks across specialties.

Simultaneously, nurse turnover has surged, particularly over the past few years, reaching nearly 20%, the highest in some time. And as labour costs rise across the board, healthcare is feeling the squeeze more than many sectors with its intensive demand for specialised medical professionals.

Soaring Labour and Operational Costs. Healthcare has not been immune to inflationary pressures. Across multiple industries, labour costs have jumped 4–5% annually. When added to the inflation loop, total cost escalations exceed 10%. For independent practices, already grappling with tight margins, this ballooning expense structure severely compresses profitability.

Squeezed Revenues Through Reimbursement Reductions. Independent provider groups relying on Medicare, Medicaid and many commercial payers are experiencing stepped-up downward pressure on reimbursement rates. Adjustments like Medicare's 3% annual fee-schedule decrease have directly cut into revenue—a hit felt acutely by smaller practices without diversified revenue streams.

Technology Overload and AI Acceleration. Doctors face rapid digital transformation—longstanding Electronic Health Records (EHR) systems, rising cybersecurity threats and an explosion of new tools like AI-based diagnostics. These innovations promise increased efficiency and improved patient care, yet they demand complex evaluation, integration and ongoing investment—costs that smaller practices struggle to meet.

The Rise of Consumerism in Healthcare. Patients are now shareholders in their healthcare journey: with high-deductible plans and online health marketplaces, they demand transparent pricing, comparative quality and even public-facing digital personas for their providers. These expectations add marketing, operational and technology requirements for independent groups; the ability to meet them varies by practice size, resources and local market.

Private Equity's Evolving Role in Healthcare

For independent groups seeking scale and financial backing without ceding identity to hospitals or insurers, private equity (PE) is one of the partnership options. This section outlines current dynamics and potential implications.. Let's explore where this trend stands—and its implications.

A Market Maturing, Not Nascent

Between 2017 and 2021, PE investment in physician practices soared: from roughly 270 transactions in 2017 to over 800 in 2021. However, with rising interest rates and reduced debt appetite, deal activity has contracted—dropping to just 250 new deals in 2024.

PE's market maturation reflects broader financial shifts. Access to cheaper debt funding is harder to come by, and many of the most promising practices have already been acquired. What remains is a mix of niche opportunities like med-spas, physical therapy clinics and outpatient infusion centres that are drawing investor interest.

Financing Pressures Impact Deal Flow

Interest rates have more than doubled since the days of near-zero rates, dramatically increasing the cost of leveraged acquisitions. As a result, PE firms are more selective and deal volume has moderated.

Acquisition Overhang

Many PE-backed healthcare platforms have hit mid-cycle—5 to 8 years post-acquisition—without achieving planned exits or payoffs. Doctors in these systems are pushing back; reports of execution fatigue in some organisations adds another drag to PE activity.

Shifting to Outpatient, Cash-Pay Sectors

With higher financing costs and reimbursement pressure, some investors are focusing on areas less affected by government payment rates, such as med-spas, dental, oncology infusion and physical therapy. These sectors offer direct pricing control (to offset labour inflation) and aren't subject to Medicare/Medicaid reimbursement lags.

Weighing the Impact: Good, Bad and Path for Success

Pros for Practices and Patients

- **Capital and infrastructure:** PE investment can enable practices to modernise systems (EHR, billing, cybersecurity), hire staff and implement technology improvements.
- **Economics:** Potential for upfront financial returns depending on transaction terms and individual circumstances.
- **Scale benefits:** Consolidation can support centralised operations, reduce administrative duplication and strengthen payer negotiations.
- **Administrative competencies:** PE may support investment in leadership, financing, revenue cycle management, technology and growth.
- **Sustaining independence:** Private equity may be structured to preserve elements of physician ownership while introducing external resources, subject to negotiated terms.

Potential Concerns

- **Workforce challenges:** According to ACP surveys, PE-owned practices often report higher staff turnover and reduced clinician autonomy, perhaps due to physicians no longer having the same degree of equity ownership.
- **Loss of control:** Clinical decisions typically remain with physicians, while back-office and administrative functions are often standardised through management service organisations (MSOs).

Factors for Consideration

- **Clinical Governance:** It is critical for physicians to retain control over all clinical decision-making of the practice without being influenced by corporate entity's pursuit of profit.
- **Joint Venture Compensation Model:** High-performing contributors will always be more productive when their compensation grows in line with the business performance.
- **Retained Equity Ownership:** Physicians should retain some ownership in the MSO to align interests and give them direct skin in the game.

PE Public Scrutiny is Perhaps Misguided

A 2024 analysis by Avalere examined Medicare use across different physician practice models. It reported **lower expenditures for patients** attributed to PE-affiliated physicians compared with those affiliated

with hospitals or corporate entities. It also noted **lower expenditures for physicians** in the 12 months after PE affiliation compared with the 12 months prior. These findings are context-specific and based on a limited sample size (Avalere 2024).

The Balancing Act: Tipping the Triple Aim

To assess partnership choices, it helps to view trade-offs through the Triple Aim. The table below outlines where value may be created or eroded across cost, quality and access.

The Road Ahead: A Middle Path?

Physician groups today face a fork in the road:

1. **Hospital/system employment**
   - *Pros:* Stability, large-scale support
   - *Cons:* Loss of autonomy, higher costs, no equity ownership
2. **Insurer/plan models**
   - *Pros:* Integrated care vision, wide platform
   - *Cons:* Vertical integration concerns, employment model, no equity ownership
3. **Private equity partnership**
   - *Pros:* Capital infusion, investment in administrative resources, may retain some equity and elements of clinical independence
   - *Cons:* Potential for differences in strategic vision, future capital transaction

Regardless of the desired path forward, physician leaders should conduct a thoughtful exploration of their strategic alternatives. This includes identifying organisational goals, assessing internal strengths and challenges, exploring multiple partnership models and conducting thorough due diligence on potential collaborators. A broad and well-informed process can help secure terms that align with the group's long-term vision and clinical priorities.

Adding Perspective

While private equity can offer capital and scale, alternative models are also emerging. Some physician groups have explored joint venture models, nonprofit affiliations, Management Service Organisations (MSOs) or cash-pay concierge conversions as ways to stay independent while modernising operations. Switching to cash pay/concierge is one model that enables providers to increase revenue while lowering their patient census to provide more one-on-one service. One market research firm estimates that concierge medicine revenue will grow about 10.4% annually through 2030 (Grand View Research 2024). MSOs are another popular strategy for physician groups to outsource administrative services to third party organisations and cut down on costs. Health system affiliations and joint ventures also provide physicians with recourses and often bring the benefit of higher insurance reimbursement rates.

> "PE investment can enable practices to modernise systems (EHR, billing, cybersecurity), hire staff and implement technology improvements."

Final Take

Independent physician practices are at a crossroads: faced with cost burdens, technological leaps, workforce stress and consumer pressure compel tough choices. Private equity offers one of potential responses to this problem, offering capital and operational support, but

Dimension	Potential Benefit	Potential Risk
Cost	Operational efficiencies, scale savings	Operating clinics like a business
Quality	Investment in systems and staff	Centralising resources and driving greater efficiencies by using more technology
Access	Expanded outpatient reach in underserved areas	Optimising underperforming locations

it also carries trade-offs that require careful evaluation. Physician leaders should assess the strategic alternatives in light of their clinical goals, community role and long-term independence. Long-term success will require a partner that preserves the mission, sustainability and local governance of the practice.

Conflict of Interest

Andrew Colbert is the Senior Managing Director in Ziegler.

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Talent Management

The Workforce Shortage in Radiology: How Do We RETAIN Our Colleagues?

Radiology faces a severe workforce shortage, with burnout driving many professionals out of the field. The RETAIN initiative addresses this by promoting leadership training and organisational strategies to enhance job satisfaction and improve retention. Through practical, evidence-based strategies and short peer-led videos, it empowers radiologists to implement positive change. While developed for radiology, RETAIN's framework can help other specialties facing similar staffing challenges.

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key points

- Radiology is facing a critical workforce shortage, driven in part by professional burnout.
- An estimated 3,100 more radiologists will be needed in the US by 2055.
- The RETAIN initiative promotes leadership training and organisational strategies to enhance job satisfaction and improve retention.
- Short peer-led videos created by radiologists share practical, evidence-based strategies to support and retain radiologists.
- RETAIN's approach is applicable across medical fields to support a resilient workforce.

Introduction

The shortage of medical professionals is not unique to the field of radiology: it is mirrored across various medical specialties. Nevertheless, radiology faces a particularly steep gap in supply and demand. As a practising radiologist in the United States, Dr. Ian Weissman witnesses these issues daily. Working alongside national organisations like the American College of Radiology (ACR) and the Radiological Society of North America (RSNA), he contributes to developing viable strategies to counteract the workforce crisis. Central to these efforts is the RETAIN initiative that provides practical, immediate measures to support and retain radiologists in their roles.

Understanding the Crisis

The radiology workforce shortage emerged as the field's most critical threat in 2023 (Ridley 2024). While the underlying causes are multifactorial, one significant factor is physician burnout—a challenge that had already been identified as the leading threat from 2019 to 2022 (AuntMinnie.com 2022). Not only does burnout drive professionals away from the field, but it also hinders performance, further straining already stretched teams.

According to the American College of Radiology's 2024 workforce data, there is currently a shortfall of approximately 1,500 radiologists in the United States. Projections are even more concerning; for example, a joint survey conducted by the ACR and the Radiology Business Management Association (RBMA), published in 2025, estimates that 3,100 additional

radiologists will be needed by 2055 to keep pace with the increasing demands for imaging (Dibble et al. 2025). Without timely and targeted interventions, this gap is likely to widen, further straining the healthcare system.

Strategic Responses

In response to the crisis, leading radiology organisations, such as the American College of Radiology's Human Resource Commission, have proposed several strategic solutions.

These include:

- leveraging artificial intelligence,
- expanding the number of postgraduate radiology residency positions,
- ensuring that international medical graduates who train in the United States are retained within the healthcare system after their education (Rawson 2024).

However, alongside these institutional and legislative efforts, there is also a need for professional-led solutions that address workplace culture, job satisfaction and long-term employee engagement. This is where the RETAIN initiative offers a distinctive contribution. Developed by Dr. Weissman, RETAIN draws on over a decade of his experience with leadership training at the Radiology Leadership Institute and Stanford Medicine's Well-Being Director's Course.

The RETAIN Initiative: A Practical Framework

The RETAIN initiative is built around a core framework of interrelated strategies:

- Retain current radiologists by fostering supportive environments.
- Educate radiology professionals in leadership and organisational strategies to counter workplace stressors and burnout.
- Train them in implementing these strategies effectively within their own practices.
- Assess the impact and outcomes of these interventions to ensure continuous improvement.
- Inquire actively about what additional support is needed to implement these changes successfully.
- New strategies are developed to deal with new challenges as they arise.

Recognising that today's professionals consume information differently (for instance, watching short TikTok and YouTube videos), RETAIN has embraced a modern format. A dedicated group of radiologists and wellness advocates has produced a series of concise, 60-second videos aimed at educating peers through accessible, engaging content. These videos, written and narrated by radiologists themselves, highlight practical, evidence-based strategies that have been successfully implemented in various institutions to boost retention and satisfaction.

> "The RETAIN initiative represents a proactive, positive step towards strengthening the radiology workforce."

Among the topics covered are:

- an introduction to the RETAIN initiative;
- methods for leveraging staff to support radiologists;
- the importance of building a positive workplace culture;
- the role of empathy in leadership;
- and the single most effective leadership strategy to retain professionals.

These resources are not only informative but also reflective of real-world experience, providing tangible insights into what works in practice.

Towards a More Resilient Radiology Workforce

The RETAIN initiative represents a proactive, positive step towards strengthening the radiology workforce. By providing practical tools and sharing evidence-based strategies, it empowers professionals to initiate positive change within their own environments. This approach not only addresses immediate concerns but also fosters a culture of support, collaboration and professional growth.

Importantly, RETAIN is not limited to senior practitioners. It is also designed to support residents and fellows, helping them identify workplace environments that align with their values and professional goals. By equipping early-career radiologists with strategies to evaluate and choose well-suited practices, RETAIN contributes to long-term career satisfaction and workforce stability.

Moreover, while developed for radiology, the RETAIN model holds relevance for other medical specialties also facing workforce challenges. Its emphasis on leadership, peer support, and positive organisational change offers a transferable framework for broader healthcare applications.

Conclusion

A recent survey by Ridley et al. reaffirmed the workforce shortage as the greatest threat facing the radiology profession today. Legislative proposals to expand residency slots and retain international medical graduates are currently under discussion in the United States, reflecting the urgency of the issue. Yet, legislative reform alone is not enough. The profession must also adopt immediate, evidence-based strategies and measures that can be implemented from within.

As we collectively work toward a prospective solution, the RETAIN initiative is a strategy that we can use immediately to educate radiologists in practical, evidence-based leadership and organisational strategies to mitigate the workforce shortage. In the future, it can help retain much-needed physicians in the profession rather than losing them to early retirement or a transfer to a new position, which is disruptive to the individual and the organisation.

Conflict of Interest

None.

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Cybersecurity

Safeguarding Patient Information: The Significance of Cybersecurity in Clinical Decision-Making

Digital transformation in healthcare has enhanced care but also increased cyber risks. With rising threats like ransomware, phishing and data breaches, clinical decision-making is jeopardised when patient data is compromised. Effective cybersecurity is now a clinical imperative, not just an IT concern, requiring robust systems, staff training and regulatory compliance to protect data integrity, availability and confidentiality across all healthcare sectors.

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key points

- Cyberattacks threaten the safety, trust and continuity of digital healthcare systems.
- Ransomware and phishing disrupt clinical workflows and delay critical patient care.
- Compromised data can lead to misdiagnoses and undermine clinical decision-making.
- Cybersecurity must be embedded across all healthcare sectors and digital tools.
- Regulatory compliance alone is insufficient without proactive, strategic security measures.

Introduction

Healthcare is the fastest-adopting digital transformation trend. Today, technology has infiltrated all aspects of the patient care continuum, from wearable biosensors to telehealth consults, from electronic health records (EHRs) to AI-driven diagnostics. Not only are these advancements raising the bar on care and care management, but they are also reshaping the way physicians receive, analyse and leverage patient information. The decisions are thus faster, smarter and more personal, since they are made in a data-rich context.

But there's a dangerous compromise being made in this digital revolution. As healthcare systems become ever more networked and data-driven, they are also growing increasingly susceptible to cyberattacks. The framework that was supposed to make clinical operations more efficient and improve patient outcomes can, if breached, compromise safety, disrupt continuity of care and erode trust between patients and providers. Cyber incidents in healthcare are no longer hypothetical risks; they are recurring events with real-world consequences. The 2017 WannaCry ransomware attack on the UK's National Health Service and the surge of attacks during the COVID-19 pandemic underscore the fragility of healthcare's digital backbone.

This two-sided coin of digitisation — at once more efficient and more vulnerable than before — represents a major new challenge for healthcare leaders. Clinical decision-making is only as reliable as the integrity of the data on which it relies. Compromised systems result in compromised data and compromised care providers in their ability to provide timely and accurate care.

In this context, unmatched cybersecurity is not a technological amenity, but a clinical necessity. All healthcare professionals have taken an Oath that every medical decision, diagnostic test and procedure starts

with the confidentiality of patient information, the integrity and availability of that information. This paper contends that cybersecurity should be regarded not simply as an IT responsibility but as a vital enabler of safe, trustworthy clinical decision-making.

The Digital Healthcare Landscape

In recent years, we have observed a swift shift towards digital healthcare, consisting of EHR, telemedicine, AI-based diagnostics and IoT-based medical devices. They provided increased efficiency in care, increased personalisation of treatment and greater access, especially in underprivileged areas.

Today, EHRs are the workhorses of hospital data systems. In the U.S., greater than 96% of non-federal acute care hospitals have adopted electronic health records (EHRs) (Office for Civil Rights 2023), and other nations, including Denmark and Estonia, cite complete national coverage. The use of telemedicine has also skyrocketed (notably during COVID-19)—global use rose over 400% from 2020 to 2022 (World Economic Forum 2024). Such tools give companies agility, but they also bring new risks as potentially sensitive information is exposed on personal, unsecured devices.

Diagnostics based on AI are poised to revolutionise sectors such as radiology and dermatology, but their accuracy is only as good as the data. A 2022 breach at a French hospital led to corrupted imaging data and diagnosis being held up for hundreds of patients (ENISA 2023). IoT medical devices—such as wearable monitors—often contain unpatched vulnerabilities and weak security protocols. More than 60% of these systems are running on obsolete software and are easily prey to attacks (HC3 2023)

These tools produce enormous volumes of data, such as an average of 50 petabytes annually in a hospital (World Economic Forum 2024) Outside of clinical care, this information is used for predictive analytics, for public health planning and drug discovery. Yet its strategic importance also makes it a prised target. Romanosky (2016), for instance, finds that health data breaches are simply more expensive than those found elsewhere due to medical records on the underground marketplace and the administrative turmoil they induce. For example, in 2020, a ransomware attack at Universal Health Services caused the system to move back to paper-based operations, significantly impacting the delivery of care (Martin et al. 2017).

Understanding the Threats and Their Impact on Clinical Decision-Making

Medical centres are now prime targets for hackers. Their immense caches of sensitive information, paired with the 24/7 pace of their operations, render them uniquely susceptible to a variety of advanced cyberattacks. Ransomware infections, for example, are one of the most common attacks in the past couple of years, as well as phishing, insider threat and vulnerabilities from third-party vendors (Kruse et al. 2017).

> "Cybersecurity should be regarded not simply as an IT responsibility but as a vital enabler of safe, trustworthy clinical decision-making."

Ransomware has emerged as the most disruptive attack vector. It is what happens when a hospital's data is encrypted by malicious software, and the attacker demands that the hospital pay a ransom to release it. One of the most prolific examples was the WannaCry breach in 2017, which risked the security of more than 80 UK NHS trusts. Operations were cancelled, ambulances diverted, patient records lost—all because of the inability to secure outdated Windows operating systems (Martin et al. 2017).

Amid the COVID-19 pandemic, the Ryuk ransomware gang also preyed on overburdened hospitals in the U.S., France and Germany. One German hospital had to turn away emergency cases, resulting in at least one death, providing a grim lesson that led to life-and-death impacts (ENISA 2023).

Phishing remains the primary method of system compromise. Stressed healthcare workers are also likely to accidentally click on fraudulent emails impersonating internal communications or official health advice. The US Department of Health & Human Services was breached through targeted phishing in 2020, boosting access

to health-related data from the COVID-19 response systems (HC3 2023).

Insider threats—whether due to malicious intent or human error—also contribute significantly to cybersecurity risks. Employees leaving data unprotected, selecting poor passwords or not adhering to security policies and procedures lay the foundation for even the most sophisticated defences to be compromised. In this regard, factors involving third parties, like breached billing systems or diagnostic providers, effectively augment the threat landscape to reach beyond the hospital's sphere of influence (Romanosky 2016).

These threats are compounded by well-known systemic flaws. Plenty of healthcare organisations use aging technology that no longer supports modern security standards. Others have poor encryption and weak identity and access management, thereby making unauthorised access a snap (World Economic Forum 2024).

The impact of these breaches is more than technical disruption, as they intrude into clinical decision-making. The data may be left inaccessible, and this lack of data can lead to a loss of both patient histories and medical records, as well as test results and medication can also result in lost medication for patients, delaying treatment and the potential for medical mistakes. If data is interfered with or corrupted, intentionally or unintentionally, it may result in misdiagnoses, wrong prescriptions, especially in systems that are based on algorithmic decision support.

Patient trust is another casualty of cyber breaches. After an incident, patients may become reluctant to share personal details, fearing misuse or exposure. This, in turn, inhibits health professional assessments and adversely affects the quality of care (Kruse et al. 2017). An analysis referenced in Martin et al. (2017) noted that more than a quarter of patients would be likely to conceal information from their health provider after a significant breach.

Data breaches can lead to disastrous consequences from a legal and monetary perspective related to institutions. Whether it's HIPAA in the U.S. or GDPR in the E.U., healthcare institutions are severely fined for non-compliance or careless data use. As per the Office for Civil Rights (2023), the average healthcare data breach cost more than €7.9 million ($9 million) in 2022, more than any other sector.

In short, cybersecurity incidents are not IT issues, they are personal safety issues, clinical accuracy issues and threats to the stability of an organisation. With the on-going digitalisation of the health service, protecting data must be viewed not as a 'compliance cost' but as a clinical responsibility, pure and simple.

"Cybersecurity incidents are not IT issues, they are personal safety issues, clinical accuracy issues and threats to the stability of an organisation."

Challenges and Vulnerabilities

Cybersecurity risks manifest differently across segments of the healthcare ecosystem, shaped by distinct operational models, technologies and regulatory contexts. Addressing these unique vulnerabilities requires a tailored approach.

- **Hospital systems** are rife with legacy infrastructure together over decades. Interoperability continues to be a challenge, especially with modern cloud-based platforms. Hospitals are also at risk, internally, because of their workforce size — hundreds or thousands of people, some of whom are more aware of cybersecurity risks than others. A crack in one ministry can expose the whole network.
- **Primary care providers and non-hospital-affiliated clinics** generally have fewer resources. Many depend on off-the-shelf systems or small IT outfits, leaving them without the resources to put up strong, multitier defences. Regular training for employees is sometimes as little as annual, along with the accompanying phishing and social engineering growth.
- **Pharmacies**, especially chain retail pharmacies, control valuable data such as prescription histories, billing information and insurance claims. Their logistics role also brings with it supply chain compromise risk. Successful hacking of a pharmacy's system would enable drug diversion, insurance fraud or counterfeit medication scams.

- **Telehealth platforms** are especially susceptible because they depend on patient-side technology — devices that are not under the control of the provider. Video consultations, data uploads and messaging functionality may not be end-to-end encrypted. Also, platform APIs are a possible attack surface, pursued by attackers to gain unauthorised data access.
- **Diagnostic laboratories** generate and retain extensive amounts of clinical and genetic information. The pace and complexity of lab operations pose challenges when cybersecurity practices are not integrated into operations. Neglected lab data may delay accurate diagnoses, influence research and introduce mistakes in patient treatment plans.
- **Health insurers** are threatened by the financial and personal information they oversee. Fraudsters frequently use claims systems to carry out fraud and steal identities. Furthermore, any failure in actuarial models or underwriting algorithms can expose systemic risks for entire population groups.

Cybersecurity as a Pillar of Clinical Integrity

Cybersecurity underpins the trustworthiness of clinical data, and the systems for interpreting and acting upon clinical data are reliable. Data integrity ensures that clinical decisions are based on accurate, unaltered information. Data availability guarantees that healthcare professionals have timely access to necessary records, while confidentiality protects patient privacy and maintains compliance with legal and ethical standards.

Clinical Decision Support Systems (CDSS), which assist healthcare professionals in diagnostic and treatment processes, are wholly dependent on accurate and real-time data inputs. If the underlying data is compromised, whether through manipulation or technical fault, CDSS output can become misleading or dangerous, potentially leading to inappropriate interventions.

The Implementation of Cybersecurity in Healthcare. Regulatory Frameworks and Compliance

The importance of data handled in health means that the healthcare sector is one of the most regulated in the world, especially in terms of clinical data management.

The Health Insurance Portability and Accountability Act (HIPAA), as well as the Health Information Technology for Economic and Clinical Health (HITECH) Act in the U.S. establish national standards for protecting health data. In Europe, the General Data Protection Regulation (GDPR) sets stringent rules on data consent, access and transfer. Also, the newer NIS2 Directive seeks to harmonise cybersecurity standards across critical sectors, including health.

When it comes to Compliance—it's not equal to security since many breaches occur in technically compliant organisations—we need a proactive security measure and continuous improvement, given by the international standards such as ISO/IEC 27799:2016 provide frameworks for building a robust information security management system tailored to data environments.

Considering this, building resilience requires not only strategy but investment and cultural change. Key practices include **Risk Assessment** (continuous evaluation of threat landscape and vulnerabilities) and adopting a **Zero-Trust Architecture** (framework that assumes no inner or outer user, device or system, can be inherently trusted), **Education and Training** and **Security by Design** (in the sense that cybersecurity must be integrated into the design of all new systems and digital health tools).

Several best practices can be found in the **Mayo Clinic** (Spain), which has implemented a layered defence strategy that combines endpoint protection, internal network segmentation, real-time anomaly detection and employee training. They also conduct regular red-teaming exercises to simulate breaches and improve incident response. Another example comes from the **Cleveland Clinic** (USA), which uses AI-powered cybersecurity solutions to monitor behavioural anomalies across its digital infrastructure. Their system can flag unusual data access patterns or external communication attempts in real-time, preventing attacks before they escalate.

Future Trends and Conclusions

New technology carries both promise and peril.Quantum computing risks making existing encryption obsolete, resulting in the need for investment in post-quantum cryptographic algorithms. Federated learning and differential privacy also enable AI models to be trained on sensitive data without revealing individual records.

For their part, patients could have greater ownership of their health data across environments with secure digital identity platforms, enhancing portability and transparency. To be effective, such advancements should be accompanied by sound governance frameworks to guarantee that these methods add value to — and do not detract from — clinical quality.

As a result, cybersecurity is not just a backend issue the IT team worries about. It is vital to safe care delivery, patient-provider trust and stability of health systems. As the healthcare industry faces digital transformation, too, we must approach securing patient data evolution.

Conflict of Interest

None.

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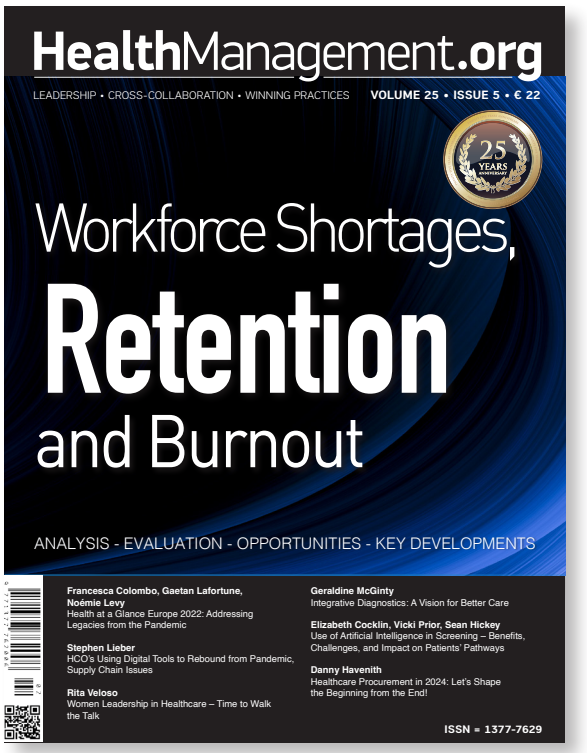

COVER STORY:

Workforce Shortages, Retention and Burnout

This issue looks into the critical challenges and best practices to overcome healthcare workforce shortages, strategies for retention and addressing burnout. It will focus on innovative solutions, including technology integration, policy changes, mental health support and organisational shifts to mitigate stress, improve wellbeing and enhance operational efficiency in healthcare environments.

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