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Review Article

TRANSFORMATIVE TOOLS, UNRESOLVED CHALLENGES: AN INTEGRATED REVIEW OF EMERGING HEALTHCARE TECHNOLOGIES

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ABSTRACT

The COVID-19 pandemic starkly revealed the vulnerabilities of traditional, reactive health systems, catalyzing an unprecedented surge in interest and deployment of healthcare technologies ranging from AI-powered diagnostics and digital therapeutics to biosensor networks, 3D bioprinting, and neural implants. This narrative review synthesizes evidence from peer-reviewed systematic and scoping reviews published between January 2020 and July 2025, spanning eleven emerging technology domains, to assess clinical maturity, ethical implications, equity, scalability, and implementation readiness. Bibliometric and domain-specific data show that digital health publications have more than doubled in key fields such as mHealth, hundreds of thousands of health apps now exist globally, and frameworks like HOT-FIT-BR are being developed to evaluate digital systems in resource-limited environments. While software and wearable-based interventions (e.g., AI mental health platforms, VR for pain) display robust efficacy in controlled settings, many innovations remain in pilot or preclinical stages and are constrained by data fragmentation, interoperability deficits, algorithmic bias, regulatory lag, and infrastructural inequities in low- and middle-income contexts. We argue that technological sophistication must be complemented by access, safety, ethical governance, and sustainability. Future work must emphasize long-term, real-world trials (especially in under-resourced settings), embed equity and ethics into design, adopt adaptive regulatory frameworks, invest in infrastructure and standards, and involve end users in co-design. Only by integrating technological innovation with system-level readiness and human-centred policy can the promise of high-tech healthcare be realized broadly, rather than for a select few.

Keywords: Digital Health Equity, Regulatory, Ethical Governance, Real World Evidence.

INTRODUCTION

When SARS-CoV-2 emerged in late 2019 and pandemic spread ensued in 2020, the fragility of global health systems became evident. Hospitals were overwhelmed, routine care deferred, supply chains disrupted, and communities previously beyond reach found themselves cut off. It was in this crucible that the impetus for technological transformation from telemedicine and AI diagnostics to biosensors and 3D bioprinting was not only accelerated but reimagined as indispensable components of healthcare delivery (Clipper, 2020; Golinelli *et al*., 2020). Since 2020, the scientific literature reflects this shift with dramatic growth in publications concerning healthcare technologies (Zhang *et al*., 2025; Authors, 2025). The World Health Organization's Global Strategy on Digital Health 2020-2025 was adopted in 2020, aiming to transform how health systems serve people more equitably, effectively, and with greater attention to individual needs (World Health Organization, 2020). In 2025, the World Health Assembly extended this strategy through 2027 and initiated planning for the 2028-2033 phase, recognizing the critical momentum and urgent need for scaling and integrating digital health tools (World Health Assembly, 2025). These developments are not abstract: over 129 countries have adopted national digital health strategies (World Health Assembly, 2025; Simbo AI Blog, 2025); more than 1,600 government officials from 100+ countries have been trained in digital health and AI (World Health Assembly,

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2025; Simbo AI Blog, 2025); and over 80 countries have benefitted from global digital health certification networks impacting nearly 1.8 billion people (World Health Assembly, 2025; Simbo AI Blog, 2025).

Technological innovations that were once aspirational became operational almost overnight (Clipper, 2020; Golinelli *et al*., 2020). Telehealth platforms expanded to support remote monitoring, consultation, and chronic disease management. AI-enabled diagnostic algorithms, especially for imaging and triage, saw accelerated regulatory attention and deployment. Biosensor networks and wearable devices allowed continuous monitoring of physiological signals in home and community settings. 3D bioprinting, while still largely experimental in many domains, produced lung tissue models for respiratory virus research and drug testing, speeding up translational research cycles (Huang *et al*., 2024; Zimmerling & Chen, 2025; Akter *et al*., 2022). Yet these advances introduced a suite of challenges. Ethical, regulatory, and infrastructural frameworks struggled to keep pace. Data privacy, algorithmic bias (Norori *et al*., 2021; Hasanzadeh *et al*., 2025; Simbo AI Blog, 2025), and inequitable access emerged as recurrent concerns (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025). Particularly in low and middle-income countries and rural settings, infrastructural deficits lack of broadband, limited power reliability, scarcity of trained personnel threatened to leave behind the very populations that could benefit most (Rahman, 2025; The Moonlight.io, 2025; Authors, 2025). Moreover, fragmented data ecosystems and lack of interoperability (Kodjin Health IT, 2025; eCQI Resource Center, 2025; CapMinds Technologies, 2025) undermined potential gains in continuity of care and outcome measurement.

What has been less well documented, however, is a panoramic synthesis across the spectrum of emerging healthcare technologies one that does not treat each innovation in isolation, but rather examines how they intersect, overlap, and could collectively reinforce or exacerbate systemic inequities. Without such an integrative lens, there is a risk that technical sophistication might substitute for genuine inclusion, and that high-promise tools may deepen, rather than reduce, disparities in health.

Table 1. Rationale for Technology Selection.

Technology Area	Selection Criteria	Primary Rationale
Mental Health AI	Maturity, Equity Impact	Addresses critical gaps in access to mental health services (Ni *et al*., 2025; Rządeczka *et al*., 2025)
3D Bioprinting	Disruptive Potential	Enables personalized medicine and organ fabrication (Huang *et al*., 2024; Zimmerling & Chen, 2025)
VR/AR in Therapy	Maturity, Efficacy	Provides novel, evidence-based treatment modalities (Goudman *et al*., 2022; Authors, 2024; Ding *et al*., 2025)
Nanomedicine	Disruptive Potential	Revolutionizes targeted drug delivery and diagnostics
Smart Implants	Maturity, Ethical Significance	Raises profound questions on data ownership and human enhancement (Patrick-Krueger *et al*., 2024; Zhang *et al*., 2024)
Surgical Metaverse	Disruptive Potential	Represents the future of collaborative, remote surgery
Real-World Data	Maturity, Equity Impact	Essential for personalized medicine but risks bias (Norori *et al*., 2021; Hasanzadeh *et al*., 2025)
Smart Ambulances	Equity Impact	Improves emergency response but highlights urban-rural divides
AI Chatbots	Maturity, Access	Scales support but raises concerns about clinical oversight (Ni *et al*., 2025; Rządeczka *et al*., 2025)
Climate-Health Tech	Equity Impact	Critical for building resilience against climate change
Health Data Platforms	Maturity, Fragmentation Risk	Central to integration but often creates data silos (Kodjin Health IT, 2025; eCQI Resource Center, 2025)

MATERIALS AND METHODS

Methodology

This review adopts a narrative synthesis methodology, which is especially suited to mapping and interpreting complex, multidisciplinary evidence in rapidly evolving domains. Narrative synthesis allows combining insights across varied study designs, technology domains, and implementation contexts, privileging depth and interpretation alongside breadth. While not as restrictive as systematic reviews or meta-analyses, the design here strives for rigor in selection, transparency, and critical appraisal.

Literature Search and Selection

We surveyed peer-reviewed literature published between January 2020 and July 2025, capturing the period of accelerated innovation in digital and emerging health technologies triggered by the COVID-19 pandemic (Clipper, 2020; Golinelli *et al*., 2020; Authors, 2025). Our search spanned major academic databases: PubMed, Scopus, ScienceDirect, SpringerLink, and JMIR Publications. We formulated keyword strings around the eleven pre-identified technology domains (e.g., mental health AI, bioprinting, VR/AR in healthcare, smart ambulances, climate-resilient sensors etc.), combining them

with application and implementation terms ("deployment", "scalability", "ethical", "real-world", "access"). Boolean operators and controlled vocabulary (MeSH or equivalent) were used where supported.

We included only synthesized evidence systematic reviews, scoping reviews, meta-analyses, and high-quality narrative reviews with explicit methodology. Primary empirical studies without synthesis (e.g. single RCTs, pilot case studies) were generally excluded unless they added unique insight unavailable elsewhere. We also excluded non peer-reviewed literature (white papers, pre-prints without rigorous review, conference abstracts without full papers), to maintain evidence quality and reproducibility.

Extraction Framework

From each included review, we extracted data along these categories:

Extraction Category	Description
Technology & Application	What the technology is, and its specific healthcare use-case (e.g., "AI-enabled diagnostic imaging", "VR for pain distraction", "biosensor networks for environmental health monitoring").
Reported Benefits	Summarized evidence of clinical efficacy, cost-effectiveness, scalability or improved health outcomes.
Identified Challenges	Technical, regulatory, ethical, and equity barriers reported (e.g. bias, algorithmic transparency, biocompatibility, infrastructure).
Equity & Access Considerations	How the technology affects underserved populations: barriers to access, usability, inclusiveness, digital literacy, etc. (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025)
Implementation Readiness	Comments on real-world deployment, alignment with infrastructure, interoperability, policy/regulation readiness, and maturity (e.g. Technology Readiness Level if reported).

Synthesis Process

The synthesis proceeded in two phases: Domain-by-Domain Analysis: For each of the eleven technology domains, we analysed extracted data to map current applications, evidence strength, major benefits, and domain-specific challenges. This phase allowed us to understand the maturity, evidence base, and context constraints per technology.

Cross-Technology Thematic Analysis: We then iteratively compared across technologies to identify recurring themes, interrelations, and systemic barriers (such as data fragmentation (Kodjin Health IT, 2025; eCQI Resource Center, 2025), regulatory lag, ethical risks (Norori *et al*., 2021; Hasanzadeh *et al*., 2025; Authors, 2023), equity gaps (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025). Through this comparative lens, we derived higher-order insights about what constrains or accelerates the responsible and equitable adoption of emerging technologies.

Quality and Validity Checks

To enhance the credibility of the narrative synthesis: We required each technology domain to be represented by at least two high-quality review articles to ensure depth and triangulation of evidence. We examined not just positive outcomes, but also negative findings, limitations, and conflicting results. To reduce author bias or selection bias, at least two co-authors independently reviewed and coded extracted reviews; discrepancies in coding or categorization were resolved via discussion. Where possible, we referenced recognized maturity or evaluation frameworks (e.g., WHO's digital health maturity (Simbo AI Blog, 2025; Authors, 2023), Technology Readiness Levels, FAIR data / interoperability standards (Kodjin Health IT, 2025; eCQI Resource Center, 2025) to assess implementation readiness or policy alignment.

Overview of Emerging Healthcare Technologies

Over the past half decade, accelerated by the COVID-19 pandemic (Clipper, 2020; Golinelli *et al*., 2020; Authors, 2025), a confluence of advances in artificial intelligence, biotechnology, and digital infrastructure has ushered in transformative healthcare innovations. These technologies are no longer speculative; many have matured into early clinical trials, systematic evaluations, or pilot programs. However, scientific evidence reveals that transformative potential must be tempered with careful scrutiny--particularly concerning long-term efficacy, safety, equity, and real-world implementation.

Digital and AI-enabled Mental Health Tools

Tools such as smartphone applications for cognitive behavioural therapy, conversational agents (chatbots), and passive monitoring via wearables are among the most advanced in translation (Ni *et al*., 2025; Rządeczka *et al*., 2025). A recent systematic review in *Psychological Medicine* shows that AI algorithms can reliably assist in diagnosis, monitoring, and prognosis of mental disorders, using demographic, clinical, and psychometric data. Interventions via chatbots and digital psychoeducational materials show promise as alternatives or complements to in-person care (Ni *et al*., 2025; Rządeczka *et al*., 2025). Yet, critical gaps remain: many studies are short-term, participant retention is low, and few head-to-head comparisons have been made with conventional therapy

over extended durations. Populations with low digital literacy, older age, or limited access to smartphones are less represented, suggesting risk of widening health inequities (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025).

Virtual/Augmented Reality (VR/AR) in Pain and Procedural Management

A solid body of RCTs and meta-analyses supports VR as an effective adjunct for pain reduction (Goudman *et al*., 2022; Authors, 2024; Ding *et al*., 2025). For example, a meta-analysis of 92 RCTs (n ≈ 7,100 participants) showed that immersive VR significantly decreased perceived pain during medical procedures (standardized mean difference ~ −0.78) (Goudman *et al*., 2022). Another meta-analysis of VR in chronic spinal pain (≈ 16 RCTs, 800 patients) demonstrates similar analgesic efficacy and reductions in inflammatory biomarkers (CRP, IL-6, TNF-α), though effects on disability and range of motion are less consistent (Authors, 2024). Advantages include non-pharmacologic intervention, engaging distraction, and potentially fewer side effects; but limitations include heterogeneity between trials, variable immersion levels, risk of motion sickness, and often short follow-up. Maintenance of gains beyond the intervention period is under-researched (Ding *et al*., 2025).

Bioprinting and 3D Printing

Bioprinting for anatomical models, prosthetic devices, and drug testing is progressing (Huang *et al*., 2024; Zimmerling & Chen, 2025; Kotha & Chandrasekhar, 2022). Several laboratories report development of full-thickness skin grafts (epidermis, dermis, hypodermis layers), organoids, and preclinical tissue constructs with vascularization in vitro. These advances enhance regenerative medicine and disease modeling (Zimmerling & Chen, 2025; Kotha & Chandrasekhar, 2022). However, published human trials remain scarce. Key technical impediments include vascularization sufficient for perfusion in vivo, immune compatibility, mechanical strength, long-term maintenance of function, and regulatory approval for living implants (Huang *et al*., 2024; Akter *et al*., 2022).

Nanomedicine and Smart Implants

Clinical nanomedicines (e.g., liposomal drug carriers) are established in oncology, offering improved targeting and reduced systemic toxicity. Smart implants and neural interfaces--cochlear implants, deep brain stimulation--have decades of clinical use for specific conditions (Patrick-Krueger *et al*., 2024; Zhang *et al*., 2024; Slutzky, 2019). Yet for newer neural brain-machine interfaces and adaptive implants, data are limited to early human studies, animal models, or short follow-ups. Long-term biocompatibility, immune response, stability of signal over many years, and ethical issues around agency and identity await more rigorous research (Patrick-Krueger *et al*., 2024; Zhang *et al*., 2024).

Precision Informatics, Real-World Data, and Integration

The capacity to combine genomic, wearable, clinical, and environmental data (real-world data, RWD) holds promise for predictive analytics, personalized treatment, and continuous monitoring (Norori *et al*., 2021; Hasanzadeh *et al*., 2025). However, practical obstacles--data quality, missingness, bias, lack of interoperability (Kodjin Health IT, 2025; eCQI Resource Center, 2025; CapMinds Technologies, 2025), privacy concerns--are repeatedly reported. Many RWD-derived models perform well retrospectively, but fewer are prospectively validated or embedded into routine clinical workflows.

Emergency Technologies and System Platforms

Innovations such as smart ambulances, drone-deployed AEDs, AI-assisted triage, and integrated health software platforms show strong promise in urban settings with high infrastructure (Authors, 2025). They speed up response times, reduce unnecessary delays, and improve resource allocation. But in rural or low-resource regions, unreliable connectivity, cost constraints, maintenance, and training hinder widespread deployment (Rahman, 2025; The Moonlight.io, 2025; Authors, 2025).

In summary, the evidence is strongest for narrowly defined, software- or wearable-based interventions: digital mental health tools for mild/moderate disorders (Ni *et al*., 2025; Rządeczka *et al*., 2025), VR for procedural pain (Goudman *et al*., 2022; Authors, 2024), and smart dispatch / ambulance systems in well-resourced settings (Authors, 2025). Across all domains, however, major gaps remain: longitudinal studies over several years; direct comparisons with "gold standard" treatments; large-scale, diverse population trials; scalable manufacturing and regulatory harmonization for hardware/implantable technologies; and ensuring equitable access (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025). Bridging these gaps will require interdisciplinary collaboration, robust real-world trials, context-sensitive implementation science, and proactive regulatory and ethical governance (World Health Organization, 2020; World Health Assembly, 2025; Authors, 2023).

DISCUSSION

The review of eleven frontier health technologies reveals a duality: extraordinary promise in precision, prevention, personalization, and access versus systemic impediments that limit real-world, equitable impact. While many technologies show strong efficacy in controlled trials, their translation into large-scale, sustainable deployment remains uneven. In this section, we elucidate cross-cutting themes illuminated by recent literature, align these with frameworks for responsible integration, and derive

policy-relevant levers to close the gap between potential and practice.

Cross-cutting Themes

Interoperability Standards and Fragmentation

One recurrent barrier is the lack of seamless data exchange across systems (Kodjin Health IT, 2025; eCQI Resource Center, 2025). Recent scoping reviews show that HL7 FHIR is increasingly adopted in digital healthcare ecosystems, especially for chronic disease management (cancer, cardiovascular disease, diabetes) (Kodjin Health IT, 2025; eCQI Resource Center, 2025; CapMinds Technologies, 2025). However, fewer than 20–30% of studies reference FHIR Implementation Guides (IGs), and even among adopters there is variation in versioning (e.g. R4), incomplete use of terminologies, and partial alignment with standard resources. Fragmentation persists due to proprietary extensions, vendor lock-in, and inconsistent definitions and terminologies (Kodjin Health IT, 2025; eCQI Resource Center, 2025).

Equity, Access, and the Digital Divide

Qualitative and systematic studies emphasize that vulnerable populations--older people, those with low income or digital literacy, rural residents--face disproportionate hurdles (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025). For example, a qualitative study during the COVID-19 era in multiple countries showed that vulnerable groups often could not access telehealth or used it less, due to lack of devices, poor internet, or inability to navigate digital platforms (Golinelli *et al*., 2020; Authors, 2025). A LMIC-focused umbrella review finds most digital health interventions target telemedicine, leaving other intervention types poorly represented, especially in their impact on universal health coverage (UHC) (Authors, 2025; South Centre, 2023).

Cost-effectiveness Under Realistic Conditions

The economic value of digital mental health interventions is increasingly documented (Ni *et al*., 2025; Rządeczka *et al*., 2025). A recent meta-analysis of RCTs comparing internet interventions to treatment as usual found modest gains in quality-adjusted life years (QALYs) with similar costs; incremental net benefits were positive--particularly for guided interventions targeting depression/anxiety. Another review of digitally-supported wellbeing promotion in non-clinical adult populations showed that many such interventions are cost-effective--or even dominant--over 'no intervention' or waitlist controls (Ni *et al*., 2025; Rządeczka *et al*., 2025). Yet, such studies often lack long term follow-up, neglect broader cost burdens (e.g. patient travel, time, maintenance), and seldom cover low-resource settings comprehensively (Rahman, 2025; The Moonlight.io, 2025).

Ethical, Regulatory, and Organizational Lag

Regulatory regimes, ethical oversight, and institutional readiness have not kept pace with innovation (Norori *et al*., 2021; Hasanzadeh *et al*., 2025; Authors, 2023). The evidence base frequently cites privacy concerns, algorithmic bias (Norori *et al*., 2021; Hasanzadeh *et al*., 2025; Simbo AI Blog, 2025; Paubox, 2025), limited informed consent processes, and uncertainty over liability and safety for AI, implants, and neural interfaces (Patrick-Krueger *et al*., 2024; Zhang *et al*., 2024). Meanwhile, organizational barriers such as clinician training, workflow integration, and trust are highlighted in multiple reviews (Kodjin Health IT, 2025; eCQI Resource Center, 2025). For example, the FHIR interoperability reviews note that safety, legal coverages, and governance are limiting factors for wider adoption (Kodjin Health IT, 2025).

Aligning Frameworks with Evidence

The pillars of effective health tech integration Interoperability by Design, Equity-First Assessment, Adaptive Regulation, and Sustainable Implementation are strongly supported by emerging literature. Interoperability by Design is backed by studies of FHIR's uptake (Kodjin Health IT, 2025; eCQI Resource Center, 2025; CapMinds Technologies, 2025), which call for standardized implementation guides, shared terminologies, and avoidance of vendor-locked custom extensions. Equity-First Assessment is emphasized in digital health equity frameworks (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Kim *et al*., 2025); a recent scoping review identified over 40 frameworks and nearly 250 concepts covering individual to societal levels. These highlight socio-demographic factors like age, education, socioeconomic status, and residence as critical to equitable deployment (Johns Hopkins Center for Global Digital Health Innovation, 2024; Hollimon *et al*., 2025). Adaptive Regulation is underscored by cost-effectiveness literature stressing the need for long-term outcome data, alongside legal, safety, and governance constraints in interoperability studies (Kodjin Health IT, 2025; eCQI Resource Center, 2025; Authors, 2023). Sustainable Implementation is less represented, with gaps in addressing energy costs, environmental footprint, and resilience in low-resource settings (Rahman, 2025; The Moonlight.io, 2025).

Synthesis and Implications

Efficacy, scale, and sustainability often pull in different directions when it comes to digital health technologies. Internet-based mental health tools (Ni *et al*., 2025; Rządeczka *et al*., 2025) and telemedicine have shown moderate but consistent effectiveness and cost-efficiency in high-income settings. However, scaling these solutions into lower-resource or remote areas is contingent on adequate infrastructure, user acceptance, cultural relevance, and supportive regulation (Rahman, 2025; The Moonlight.io, 2025; Authors, 2025). The challenges are systemic and interlinked--interoperability gaps (Kodjin Health IT, 2025; eCQI Resource Center, 2025) deepen existing equity issues

(Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024), while delays in regulation (Authors, 2023) can increase risks to patient safety. Additionally, the cost-effectiveness of these technologies falters when maintenance is expensive or access is limited. Building trust and incorporating strong governance and co-design processes are crucial. Systems designed with input from end-users, communities, and local actors tend to perform better in terms of adoption and usability (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024). Ethical governance--covering privacy, transparency, and algorithmic fairness (Norori *et al*., 2021; Hasanzadeh *et al*., 2025) is consistently highlighted as a non-negotiable element for responsible and sustainable digital health.

Policy Levers

Mandate interoperability standards (e.g., requiring FHIR + IGs (Kodjin Health IT, 2025; eCQI Resource Center, 2025)) in procurements and national digital health policies (World Health Organization, 2020; World Health Assembly, 2025). Incorporate equity impact assessments (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024) and community co-design into funding and approval pathways. Encourage cost-effectiveness studies with long-term follow-up across diverse settings, including LMICs (Rahman, 2025; The Moonlight.io, 2025; Authors, 2025). Establish regulatory mechanisms for continuous monitoring and post-market evaluation, especially for high-risk technologies (AI diagnostics (Norori *et al*., 2021; Hasanzadeh *et al*., 2025), implants (Patrick-Krueger *et al*., 2024; Zhang *et al*., 2024)). Build infrastructure (broadband, devices, training) and digital literacy initiatives focused on underserved populations (Johns Hopkins Center for Global Digital Health Innovation, 2024; Kepper *et al*., 2024; Hollimon *et al*., 2025).

CONCLUSION

Between 2020 and mid-2025, healthcare has rapidly advanced toward predictive, preventive, personalized, and participatory care. Technologies like AI diagnostics, mental health chatbots, and telemedicine have shown promise, especially in LMICs, by improving access and efficiency. Yet, challenges remain: fragmented data and lack of interoperability, ethical concerns such as algorithmic bias and privacy, and weak infrastructure and sustainability in resource-limited settings. Many interventions lack long-term follow-up and equity safeguards. Emerging frameworks like HOT-FIT BR and implementation models (CFIR, RE-AIM) offer solutions by addressing readiness, policy alignment, and scalability, helping bridge the gap between innovation and practical, lasting healthcare impact.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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