Navigating the Evolution of Digital Twins and the Metaverse for Lasting Impact on Consumer Health

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Abstract. Digital twins and the metaverse have emerged as revolutionary technologies, with significant potential to transform consumer health by enabling personalized medicine, virtual care, and improved patient outcomes. However, sustaining these digital solutions over time requires careful consideration of various factors such as technological advancements, user needs, regulatory requirements, and ethical considerations. This book chapter aims to provide insights into navigating the evolution of digital twins and the metaverse in consumer healthcare to ensure lasting impact.

This chapter explores the challenges and opportunities associated with ensuring long-term viability and maintenance of digital twin technology and the metaverse within the context of consumer health. It begins by examining the current state of digital twins and the metaverse in healthcare, highlighting successful case studies that demonstrate their utility in improving patient outcomes and experiences. Next, it discusses key trends shaping the future of these technologies, including artificial intelligence (AI), machine learning (ML), Internet of Things (IoT) devices, blockchain, and extended reality (XR). Additionally, this chapter delves into critical issues surrounding data privacy and security, interoperability, standardization, and scalability, providing recommendations for addressing them. Finally, the chapter concludes by outlining best practices for designing sustainable digital twin and metaverse ecosystems, emphasizing the importance of ongoing research, development, and collaboration among stakeholders. By following these guidelines, healthcare providers can harness the full potential of digital twins and the metaverse while fostering innovation, enhancing efficiency, and promoting better health outcomes for consumers.

Keywords: Digital Twins· Metaverse· Consumer Health· Sustainability· Technology Evolution· Interoperability· Standardization · Data Privacy· Security· Scalability· Collaboration.

1 Introduction to Digital Twins and the Metaverse

Digital twins and the metaverse are two emerging concepts that have been gaining significant attention in recent years. Both technologies hold immense potential for transforming various sectors by providing immersive experiences and enabling digital representations of physical entities[1]. In this introduction, we will explore each concept individually before discussing their convergence and possible implications[2].

Digital Twins: Virtual Replicas of Physical Entities A digital twin can be defined as a virtual representation of a physical object or system, capable of mirroring its actual state and behavior through continuous synchronization with real-world data streams (Gartner). By integrating IoT devices, sensors, artificial intelligence, machine learning algorithms, and advanced analytics tools[13], digital twins create an accurate simulation environment where users can monitor performance, optimize processes, detect anomalies, perform predictive maintenance, and even conduct experiments without affecting the original entity. This enables organizations to reduce costs, increase efficiency, enhance safety, and improve decision-making across different domains like manufacturing, transportation, energy management, construction, healthcare, agriculture, and more[4].

Key Components of Digital Twins

Physical Asset: A tangible entity or system subjected to measurement and control via connected sensors and actuators. Examples include machines, buildings, vehicles, infrastructure networks, medical equipment, etc. Virtual Model: A digitized counterpart of the physical asset, created using CAD software, simulations, and other modeling techniques. It represents the structure, properties, functions, and interactions of the corresponding physical entity[5]. Data Connectivity Communication: Real-time communication between the physical asset and its virtual model utilizing IoT protocols, APIs, and middleware platforms ensures seamless information exchange. Analytics Engine: Advanced analytic capabilities powered by AI, ML, and big data processing techniques help interpret collected data, generate insights, identify patterns, and make predictions about the physical asset's future condition and performance. User Interface: An intuitive interface allows operators, engineers, designers, and managers to interact with the digital twin, visualizing its current status, historical trends, and predicted outcomes[6].

Applications of Digital Twins

Predictive Maintenance: Continuous monitoring of equipment health and proactive identification of potential failures reduces downtime and increases productivity. Process Optimization: Simulation environments facilitate experimentation, testing new configurations, and identifying optimal settings for improved operational efficiency[7]. Remote Monitoring: Operational oversight from distant locations becomes feasible, reducing travel requirements and response times while enhancing security measures. Design Validation: Early detection of design flaws minimizes costly iterations during development stages and ensures better product quality[8].

2 Understanding Consumer Health in the Digital Era

In today's rapidly changing technological landscape, consumer health has taken on a whole new meaning. The advent of digital tools and resources has enabled individuals to actively participate in managing their own wellbeing, leading to what can be described as 'consumer health in the digital era'. This shift towards self-empowerment is characterized by increased accessibility, affordability, and convenience of health-related information and services.

Smartphones, wearable devices, and Internet of Things (IoT)-enabled gadgets serve as gateways to tracking biometric parameters such as heart rate, blood pressure, sleep patterns, activity levels, and caloric intake. These tools provide real-time feedback, encouraging users to adopt healthier lifestyles and make informed choices regarding their diet, exercise routines, stress management strategies, and overall lifestyle habits. Moreover, advancements in artificial intelligence (AI) and machine learning (ML) algorithms allow for customized coaching, motivational nudges, and personalized guidance tailored to individual needs and preferences[9].

Telemedicine platforms represent another critical aspect of consumer health in the digital age. Video conferencing, messaging apps, and remote patient monitoring systems bridge geographical gaps, enabling patients to connect with healthcare professionals irrespective of location. Such virtual consultations offer several advantages, including reduced waiting times, lower transportation costs, enhanced comfort, and decreased exposure to infectious diseases. Furthermore, electronic health records (EHRs) centralize patient data, facilitating comprehensive care coordination and streamlined communication amongst multi-disciplinary teams.

Online support communities constitute yet another essential component of consumer health in the digital era. Social media groups, discussion forums, and peer-to-peer networking sites foster connections among people facing similar health challenges, promoting mutual understanding, empathy, and encouragement. Additionally, numerous websites, blogs, podcasts, and e-learning courses cater to specific health interests, disseminating evidence-based knowledge and fostering greater awareness.

However, along with these benefits come certain challenges and risks associated with consumer health in the digital age. Data privacy and security remain paramount concerns due to the sensitive nature of health-related information. Ensuring robust encryption mechanisms, transparent consent procedures, and stringent regulatory compliance is imperative for safeguarding user confidentiality. Another challenge pertains to the accuracy and reliability of digital health tools and resources – rigorous validation studies, clinical trials, and independent evaluations must be conducted prior to market deployment to ascertain efficacy and minimize harm. Lastly, striking an appropriate balance between human expertise and algorithmic automation prevents undue reliance on technology at the expense of professional judgment and nuanced decision-making[10].

3 Evolution of Digital Twins in Healthcare

The evolution of digital twins in healthcare marks an exciting milestone in the fusion of technology and medicine, offering unprecedented possibilities for enhancing patient care, accelerating research breakthroughs, and revolutionizing treatment paradigms. Initially conceived within industrial settings, digital twins have gradually permeated the realm of healthcare, demonstrating remarkable potential across various application areas[11].

At the vanguard of digital twin adoption in healthcare stands personalized medicine, where virtual models mirror individual physiological characteristics and genetic traits. By incorporating genomic data, epigenetic factors, proteomics profiles, and environmental exposures, these highly sophisticated avatars enable precision diagnostics, targeted therapeutics, and stratified intervention strategies tailored to unique patient attributes. For instance, researchers at the University of Pennsylvania developed a digital twin platform to simulate tumor growth dynamics based on individual mutational landscapes, thereby informing optimal cancer therapy combinations (Clermont et al., 2017). Similarly, investigators at MIT engineered computational models mimicking cardiac electrophysiology, facilitating personalized risk assessment and preemptive action against life-threatening arrhythmias (Pathmanathan et al., 2018)[12].

Another prominent domain witnessing the emergence of digital twins pertains to surgical planning and rehearsal. Surgeons employ these virtual constructs to meticulously map operative pathways, anticipate anatomical variations, and evaluate alternative approaches, thereby mitigating procedural complications and expediting recovery times. Notably, Surgical Theatre - a California-based startup - introduced a proprietary platform merging CT scans, MRI images, and angiographic data to generate three-dimensional renderings of patient-specific vasculature, subsequently guiding surgeons through intricate neurovascular procedures (Surgical Theatre, n.d.). Likewise, UK-based Touch Surgery devised an app harnessing AR technology to recreate realistic operating room scenarios, enabling practitioners to hone technical skills and bolster proficiency in minimal invasive techniques (Touch Surgery, n.d.)[13].

Prosthetics and implantable device design constitutes yet another fertile ground for digital twin implementation. Researchers exploit detailed anatomic replicas to optimize mechanical designs, material selection, and functional features, culminating in superior fit, durability, and biocompatibility. Recently, scientists at ETH Zurich pioneered a biohybrid soft robotics gripper inspired by octopus tentacles, which dynamically adapts to varying load conditions and exhibits exceptional adaptability in diverse tasks (Cianchetti et al., 2018). Meanwhile, medtech companies such as Medtronic leverage digital twin technology to remotely monitor pacemaker functionality, foresee impending malfunctions, and instigate prompt corrective measures (Medtronic, n.d.)[14].

Lastly, digital twins find utility in population health management, particularly amid escalating public health crises like COVID-19 pandemic. Public health authorities utilize aggregate-level models to forecast infection rates, allocate scarce resources judiciously, and implement targeted containment strategies,

thereby minimizing societal disruption and economic consequences. Renowned epidemiologist Neil Ferguson and colleagues at Imperial College London garnered international acclaim for their agent-based simulation tool estimating transmission dynamics and projecting hospital demand during the initial phase of the outbreak (Ferguson et al., 2020)[15].

Despite these notable achievements, several barriers impede wide-scale diffusion of digital twins in healthcare. Foremost among them includes prohibitive costs, fragmented datasets, and dearth of standardized methodologies governing creation, curation, and sharing of virtual models. Addressing these challenges entails concerted efforts from multidisciplinary stakeholders, spanning academia, industry, governments, and civil society. Emphasis on open-source platforms, collaboration networks, and cross-sector partnerships catalyzes innovations, fuels entrepreneurship, and stimulates translational research endeavors, ultimately propelling digital twins toward mainstream acceptance and utilization in healthcare.

4 The Emergence of the Metaverse and Its Influence on Consumer Health

The emergence of the metaverse heralds a revolutionary transformation in consumer health, engendering immersive experiences, ubiquitous connectivity, and decentralized architectures that transcend traditional boundaries between physical and digital worlds. Rooted in the amalgamation of extended reality (XR) technologies, namely virtual reality (VR), augmented reality (AR), and mixed reality (MR), the metaverse promises to reshape healthcare delivery, research, and policy formulation by democratizing access, fostering inclusivity, and cultivating personal responsibility[16].

One salient feature characterizing the metaverse vis-à-vis consumer health pertains to gamification—the strategic infusion of game mechanics into non-ludic contexts. Gamifying health behaviors incentivizes active participation, promotes sustained engagement, and reinforces desirable habits by tapping into innate psychological drivers such as curiosity, competition, achievement, and social affiliation. Exemplars abound in this nascent sphere, ranging from exergames designed to combat sedentary lifestyles, mobile apps targeting mental health issues, and web-based platforms addressing substance use disorders. Indeed, early evidence suggests that gamified interventions yield comparable or superior outcomes relative to conventional methods, warranting serious consideration from policymakers, practitioners, and payers alike (Brivio et al., 2018; Hamari et al., 2016)[17].

Additionally, the metaverse holds considerable promise for expanding telediagnostic and teletherapeutic modalities. Leveraging high-fidelity sensory inputs, real-time data streaming, and haptic feedback loops, remote consultations become virtually indistinguishable from face-to-face encounters, thus obviating spatial constraints imposed by brick-and-mortar facilities. Telehealth applications extend beyond mere videoconferencing sessions, encompassing specialized niches such as virtual occupational therapy sessions, remote wound assessments, and

AI-assisted triage systems. Furthermore, blockchain-powered distributed ledger technologies enable secure, tamper-proof recordkeeping, ensuring data integrity, portability, and interoperability across disparate jurisdictions (Dubovitskaya et al., 2020)[18].

Moreover, the metaverse provides fertile ground for cultivating patient advocacy, community building, and peer-to-peer support networks. Mirroring real-world affinity group dynamics, virtual gatherings furnish safe spaces where individuals share lived experiences, exchange coping strategies, and derive solace from kindred spirits navigating analogous journeys. By bridging geographical divides, linguistic barriers, and cultural chasms, the metaverse fosters global solidarity and amplifies marginalized voices, potentially galvanizing grassroots movements advocating for meaningful change in healthcare policy, financing, and governance (Kim et al., 2018).

Notwithstanding these tantalizing prospects, several caveats temper enthusiasm surrounding the metaverse and consumer health. First, inequitable access to requisite hardware, software, and network infrastructure may exacerbate existing disparities, perpetuating cycles of poverty, exclusion, and stigma. Second, lax regulation and insufficient oversight raise valid concerns about privacy violations, cybersecurity breaches, and unethical business practices that could erode public trust and compromise patient welfare. Third, excessive screen time, addiction, and detachment from corporeal existence pose substantial threats to psychosocial wellbeing, necessitating thoughtful boundary-setting and mindfulness training (Przybylski, 2014)[19].

Addressing these challenges demands concerted efforts from diverse stakeholders spanning private enterprise, government agencies, academic institutions, and civic societies. Specifically, four key principles ought to guide responsible development and deployment of metaverse technologies in pursuit of improved consumer health: equity, transparency, agency, and sustainability. Adhering to these tenets implies investing in inclusive design, engaging in honest dialogues concerning risks versus rewards, empowering users to shape their digital footprints, and conserving finite resources for posterity. Ultimately, realizing the full potential of the metaverse depends crucially upon our ability to strike a delicate balance between progress and preservation, innovation and tradition, vision and pragmatism[20].

5 Integrating Digital Twins and the Metaverse for Health Enhancement

The integration of digital twins and the metaverse has significant potential to enhance health outcomes. A digital twin is a virtual representation of a physical object or system, while the metaverse is a collective virtual shared space that is created by the convergence of virtually enhanced physical reality and physically persistent virtual reality. By combining these two technologies, it becomes possible to create highly detailed, interactive simulations of real-world environments and systems, which can be used to improve health in a number of ways.

One key area where this technology could have a major impact is in the field of healthcare simulation. With digital twins, medical professionals can create accurate models of individual patients, complete with their specific physiology, medical history, and other relevant data. These digital twins can then be used to simulate various treatment options and scenarios, allowing doctors and nurses to practice procedures and make more informed decisions about patient care. This can lead to improved patient outcomes, as well as reduced costs associated with errors and complications.

The metaverse also offers opportunities for remote collaboration and consultation between healthcare providers. For example, surgeons in different locations could use the metaverse to work together on complex cases, sharing knowledge and expertise in real time. This would allow specialists from around the world to collaborate on difficult surgeries, potentially leading to better results for patients. Additionally, patients themselves could access the metaverse to receive consultations and follow-up appointments remotely, reducing the need for travel and making healthcare more accessible[21].

Another important application of digital twins and the metaverse in health enhancement is in the realm of public health. Virtual representations of entire communities or even cities can be created using digital twin technology, allowing officials to model and analyze the spread of diseases and identify areas where interventions may be needed. This information can then be used to develop targeted strategies for disease prevention and control, ultimately improving overall population health.

In addition to its applications in healthcare delivery and public health, digital twin technology combined with the metaverse also holds promise for research and development. Scientists can use these tools to study human biology and disease processes at an unprecedented level of detail, paving the way for new treatments and therapies. Furthermore, the ability to create realistic virtual environments allows researchers to test out new drugs, devices, and procedures before they are ever tried on humans, reducing risk and increasing safety[22].

However, there are some challenges and concerns when integrating digital twins and the metaverse for health enhancement. One such concern is privacy and security, ensuring that sensitive personal health data remains protected within the virtual environment. Another challenge is the cost and complexity of implementing and maintaining these advanced technological systems. Also, there's a need for standardization across platforms, so that data can be easily exchanged and integrated.

Despite these challenges, the potential benefits of integrating digital twins and the metaverse for health enhancement are clear. Through increased accessibility, improved decision-making, targeted interventions, and cutting-edge research capabilities, this technology has the power to transform healthcare and significantly improve health outcomes. As we continue to advance our understanding of both digital twin and metaverse technology, it will be essential to address any ethical considerations and ensure equitable distribution of resources to fully realize the potential of this powerful combination[23].

6 Challenges and Opportunities in Harnessing Digital Twins and the Metaverse for Consumer Health

Harnessing digital twins and the metaverse for consumer health presents unique challenges and opportunities. On one hand, these technologies offer promising avenues for promoting healthy behaviors, delivering personalized medicine, and enhancing patient engagement. However, there are also several obstacles that must be addressed in order to fully leverage their potential.

Challenges:

1.Data Privacy and Security: Protecting consumers' private health information is paramount, especially given the sensitive nature of much of the data involved. Robust cybersecurity measures must be implemented to prevent unauthorized access and breaches. Moreover, transparent communication regarding how data is collected, stored, and utilized is crucial to build trust with users[24].

2.Regulatory Compliance: Navigating regulatory frameworks poses another challenge. While existing regulations cover traditional healthcare services, novel applications like digital twins and the metaverse often fall outside established guidelines. Adapting current legislation or creating new ones to accommodate these emerging technologies is necessary to ensure compliance and protect consumers.

3.Equity and Accessibility: There is a risk that these innovations might widen disparities if only adopted by certain demographics due to factors like affordability or technical literacy. Efforts should focus on developing user-friendly solutions and addressing barriers to entry to promote inclusivity and equal access to digital health tools.

4.Ethical Considerations: Balancing innovation with ethics requires careful consideration. Issues surrounding consent, transparency, accountability, and fairness should be taken into account during design and implementation phases. Regular reviews and updates to policies will help maintain responsible practices as technology evolves.

Opportunities:

1.Personalized Medicine: Tailored treatments based on each individual's genetic makeup, lifestyle, and environmental factors can become a reality through digital twin modeling. This enables clinicians to predict responses to medications, tailor dosages, and optimize therapeutic regimens, resulting in improved clinical outcomes and reduced adverse effects.

2.Remote Monitoring and Telehealth: Digital twins and the metaverse enable continuous monitoring of vital signs, symptoms, and progress without requiring frequent hospital visits. Real-time feedback empowers patients to manage chronic conditions effectively, reduce readmissions, and lower healthcare costs[25].

3.Behavior Change Interventions: Immersive experiences offered by the metaverse provide engaging methods for reinforcing positive behavior changes related to exercise, nutrition, stress management, and medication adherence. Gamification elements can further motivate users towards achieving their health goals.

4.Education and Training: Professional education, patient empowerment, and community awareness programs can benefit immensely from the experiential

learning provided by the metaverse. Highly realistic simulations facilitate skill acquisition, retention, and transfer, thereby fostering competency among healthcare workers and laypeople alike.

5.Research and Development: Large-scale, longitudinal studies incorporating digital twin models and metaverse simulations offer valuable insights into disease mechanisms, drug efficacies, and intervention effectiveness. Such evidence generation supports rapid translation of findings into practical applications, accelerating discovery and innovation.

7 Ethical Considerations and Privacy Safeguards in Consumer Health within the Metaverse

Ethical considerations and privacy safeguards play a crucial role in shaping the future of consumer health within the metaverse. Given the vast amounts of personal health data being generated, processed, and analyzed, protecting individuals' privacy and upholding ethical values is imperative. Herein lie some key ethical considerations and privacy safeguards that ought to be addressed:

1.Informed Consent: Obtaining meaningful informed consent from users before collecting, storing, and utilizing their health data is fundamental. Users must understand what data is being gathered, why it is required, who will have access to it, and how long it will be retained. Clear and concise language devoid of jargon facilitates comprehension and promotes autonomy.

2.Transparency and Accountability: Maintaining open lines of communication concerning data handling practices instills confidence in users. Periodically updating terms of service, disclosing algorithms employed, and providing explanations behind recommendations made strengthen transparency. Appointing independent auditors to monitor metadata usage and reporting suspicious activities bolsters accountability.

3.Fairness and Non-Discrimination: Preventing discrimination based on race, gender, age, socioeconomic status, or pre-existing conditions necessitates stringent scrutiny over algorithmic bias. Routinely evaluating machine learning models for impartiality minimizes potential harm inflicted upon vulnerable populations.

4.Beneficence and Respect for Autonomy: Prioritizing beneficent actions aligns with healthcare professional norms, wherein doing no harm guides decision-making. Empowering users to decide whether they wish to participate or withdraw from metaverse services preserves their autonomy and dignity.

8 Future Perspectives and Enduring Effects on Consumer Health

The integration of digital twins and the metaverse promises numerous exciting possibilities for consumer health. Overcoming present challenges and embracing

ethical considerations pave the way for a brighter future characterized by innovative breakthroughs, improved quality of life, and sustained societal impacts. Some anticipated future perspectives include:

1.Predictive Analytics Precision Medicine: Leveraging massive volumes of historical and real-time health data generates predictive analytics instrumental in crafting bespoke treatment plans. Personalized medicine tailors pharmacological interventions, surgical approaches, and nutritional guidance to maximize therapeutic efficacy while minimizing side effects.

2.Augmented Reality (AR) / Virtual Reality (VR) Applications: AR/VR technologies transport users to immersive environments offering myriad health benefits. Physical therapy sessions can incorporate gamified exercises designed to hasten recovery times; mental health counseling can employ relaxing landscapes to alleviate anxiety disorders; cognitive training modules can sharpen memory skills for elderly cohorts.

3.Social Connectedness Support Networks: The metaverse transcends geographical boundaries, enabling users worldwide to form supportive bonds irrespective of location. Peer support groups fostering empathy, compassion, and camaraderie cater specifically to niche health issues, breaking down isolation barriers prevalent amongst marginalized communities.

4.Public Health Surveillance Disease Management: Early detection and prompt response constitute cornerstones of effective pandemic preparedness. Digital twins simulating infectious agent transmission patterns inform policy deliberations pertinent to resource mobilization, lockdown restrictions, and vaccine rollouts. Post-pandemic recovery initiatives concentrate on revitalizing economies, restoring social fabrics, and reconstructing healthcare infrastructure.

5.AI-Driven Diagnostics Decision Making: Machine learning algorithms perusing electronic health records, radiologic images, and genomic sequences augment diagnostic accuracy, diminishing misinterpretation rates attributed to human error. Clinician judgment supplemented by artificial intelligence renders superior judgement calls culminating in favorable prognoses.

6.Telemedicine Expansion Mobile Healthcare Services: Extending telemedicine coverage caters to previously underserved regions suffering from dearth of specialized practitioners. Portable diagnostic equipment coupled with high-speed internet connectivity furnish rural inhabitants comparable healthcare access enjoyed by urban counterparts.

7.Workforce Capacity Building Skill Development: Upskilling healthcare professionals keeps pace with rapid technological advances underpinning modern medicine. Simulated training modules equip learners with requisite proficiencies demanded by dynamic market forces, elevating overall sector performance metrics.

9 Conclusion and Recommendations for Advancing Consumer Health in the Digital Twin-Metaverse Landscape

In conclusion, harnessing the immense potential of digital twins and the metaverse for consumer health demands concerted efforts from diverse stakeholders, including technologists, regulators, healthcare providers, and patients themselves. To advance consumer health in this rapidly evolving landscape, we recommend the following strategic priorities:

1.Fostering multi-stakeholder dialogues: Engaging representatives from various backgrounds catalyzes constructive debates surrounding pressing challenges, spurs creative problem solving, and cultivates shared ownership. Joint committees tasked with establishing guidelines, benchmarks, and evaluation criteria galvanize collective endeavors aimed at realizing optimal health outcomes.

2.Investing in research and development: Allocating dedicated funding streams toward exploring untapped applications, refining existing methodologies, and disseminating validated best practices fuels scientific progression. Targeted grants incentivize innovators to push boundaries, generate groundbreaking discoveries, and translate theoretical concepts into practical applications.

3.Strengthening regulatory oversight: Evolving regulatory structures adapt to accommodate disruptive technologies, balancing flexibility with rigorous validation requirements. Harmonizing international standards establishes universally accepted norms, obviating inconsistencies plaguing cross-jurisdictional collaborations.

4.Cultivating digital literacy: Bridging the digital divide entails educating consumers about available resources, dispelling common myths, and empowering them to navigate emergent digital health ecosystems confidently. Phased introductions scaffolded by adequate support networks ease transitions, minimize resistance, and encourage wider adoption.

5.Embedding ethical considerations: Foregrounding ethical tenets embedded in universal declarations of human rights ensures non-negotiable foundational pillars guiding every stage of product development, deployment, maintenance, and sunsetting. Robust governance frameworks enforce accountability, rectify lapses, and restore equilibrium swiftly whenever breaches occur.

Embracing these recommendations positions us favourably to capture latent opportunities presented by digital twins and the metaverse, revolutionizing consumer health paradigms along the journey. It bears emphasizing that success hinges on genuine partnerships anchored in mutual trust, reciprocity, and unwavering commitment to placing people at the heart of innovation. Together, we stand poised to unlock unprecedented value propositions heralding a brave new era for consumer health.

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