Review article

Transforming Healthcare Technology in Crisis: A Review of Biomedical Engineering, AI Integration, and Smart Procurement Systems

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***Abstract*— The COVID-19 pandemic exposed critical vulnerabilities in global healthcare systems, including equipment shortages, fragmented communication, inefficient procurement, and weak regulatory frameworks. Biomedical and clinical engineers were instrumental in managing and adapting medical devices under crisis conditions, highlighting the need for systematic device governance. Artificial Intelligence (AI) and Machine Learning (ML) technologies transformed diagnostics, predictive modeling, and logistics, enabling rapid, data-driven responses. Digital procurement platforms advanced, offering real-time equipment tracking and inventory optimization to address supply chain disruptions. This review examines the pivotal role of healthcare technologies during the pandemic, focusing on biomedical engineering contributions, AI/ML integration, digital platform advancements, and anti-corruption procurement frameworks. It emphasizes regulatory clarity, system interoperability, and patient safety as critical for effective technology deployment. The findings advocate for long-term strategies to build resilient, innovative healthcare infrastructures that prioritize ethical practices, operational efficiency, and robust preparedness to ensure global health systems are better equipped for future crises.**

***Keywords* — AI/ML, Biomedical engineering, COVID-19, Healthcare technology and systems, Medical equipment.**

I. INTRODUCTION

The COVID-19 pandemic placed extraordinary pressure on global healthcare systems, prompting rapid adaptations in infrastructure, medical device logistics, and emergency preparedness (Filip et al., 2022). In the United Kingdom, for instance, the centralized procurement and distribution of medical equipment enabled hospitals to quickly scale up Intensive Care Units (ICUs) capacity and address shortages of essential resources (Arabi et al., 2022; Gupta et al., 2021).

At a global scale, gaps in medical device availability, safety, and interoperability were exposed, highlighting the need for better regulatory coordination, training, and infrastructure (Gibbins et al., 2020; Aspden, 2004; WHO, 2008). The crisis also accelerated interest in digital procurement tools and AI, which emerged as enablers of smarter decision-making in diagnostics and resource management (Muehlematter et al., 2021).

This review explores the specific role of biomedical engineers in emergency responses, the importance of digital procurement and AI/ML tools, and the regulatory and infrastructure lessons learned from the pandemic. The goal is to outline practical strategies for building more resilient healthcare systems worldwide.

II. SYSTEMIC WEAKNESSES IN HEALTHCARE INFRASTRUCTURE EXPOSED BY COVID-19

The pandemic revealed fundamental vulnerabilities in healthcare infrastructure globally. Many countries, particularly low- and middle-income ones, struggled with overstretched facilities, limited medical equipment, and outdated health information systems. These weaknesses severely hindered their ability to respond effectively and equitably to the rapidly evolving crisis **(Table 1)**.

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One major shortfall was in procurement and inventory systems. In numerous settings, inefficient procurement mechanisms led to mismatches between supply and need, resulting in either shortages or overstocking of essential items like personal protective equipment (PPE), ventilators, and oxygen cylinders (McCabe et al., 2021). Health facilities lacked reliable digital infrastructure to track equipment usage, forecast demand, or redistribute resources dynamically. These issues were further exacerbated by poor data integration across hospitals and ministries, impeding coordinated responses (Culkin et al., 2023). Logistical blocks also undermined health system responsiveness. In rural and underserved regions, weak transportation networks and unreliable electricity supplies delayed the delivery and operation of critical devices, such as refrigeration units for vaccines or digital diagnostic tools (Aranda-Jan et al., 2014). In such contexts, even well-intentioned donations often remain unused due to incompatibility with local infrastructure or lack of training in use and maintenance. Moreover, many healthcare systems lacked robust biomedical engineering support to maintain and repair equipment. This gap led to the accumulation of non-functional or abandoned devices, wasting resources during critical periods of need (WHO, 2017). The absence of centralized biomedical asset inventories and standardized procurement practices further led to inefficiencies in resource allocation and delays in deployment (WHO, 2020). Digital health infrastructure deficiencies compounded these problems. Many healthcare facilities lacked Electronic Health Records (EHRs), integrated communication systems, and remote monitoring capabilities. This impeded coordinated care delivery and limited the use of data-driven technologies such as telemedicine, AI-based diagnostics, and digital triage platforms (Mukherjee et al., 2021).

Table 1: Systemic Weaknesses in Healthcare Infrastructure Exposed by COVID-19

Domain	Key Challenges	Impact on Crisis Response
Procurement & Inventory	Inefficient systems, poor tracking, mismatches between supply and need	Shortages/overstocking of PPE, ventilators, and oxygen
Data Infrastructure	Lack of integration across facilities, poor information flow	Impeded coordinated response efforts
Logistics & Distribution	Weak transportation networks, unreliable electricity	Delayed delivery of critical devices, especially in rural areas
Biomedical Engineering Support	Insufficient maintenance capacity, lack of centralized asset inventories	Accumulation of non-functional equipment, wasted resources
Digital Health	Limited EHR adoption, poor communication systems	Restricted telemedicine capabilities and data-driven decision making

III. Role of Biomedical Engineers During the COVID-19 Crisis

Biomedical Engineers (BMEs) played a pivotal role in supporting healthcare systems during the COVID-19 pandemic, contributing across diagnostics, treatment, and logistics. Unlike in pre-pandemic times, their contributions were thrust into the spotlight as they rapidly adapted, designed, or repaired essential medical equipment under intense pressure (Agu et al., 2021). A key area of involvement was the rapid development and local manufacturing of critical equipment such as ventilators, oxygen concentrators, and PPE. In regions where international supply chains were disrupted, BMEs collaborated with academic institutions, government bodies, and private industry to produce affordable alternatives tailored to local resource constraints (Bong et al., 2020). In some cases, engineers repurposed existing devices or developed open-source designs that could be shared across borders, enhancing global solidarity and adaptability (Rao et al., 2022).

Biomedical engineers were central in the assessment, repair, and repurposing of existing equipment to meet urgent needs. They contributed to the rapid development and deployment of novel technologies tailored to local constraints, such as low-cost ventilators or solar-powered oxygen concentrators. These innovations were often designed with frugal engineering principles to ensure reliability in resource-limited environments (Wang et al., 2020). In addition to manufacturing, biomedical engineers were instrumental in maintaining and troubleshooting complex devices in overwhelmed hospitals. With minimal downtime allowed, engineers ensured the safety and calibration of medical equipment, trained clinical staff on usage, and adapted imported technologies to local settings, mitigating risks of misuse or device failure (WHO, 2017). Biomedical engineers also supported the deployment of digital tools for patient monitoring, remote diagnostics, and data integration. This included work on telemedicine systems, mobile health (mHealth) applications, and sensor networks to assist with contact tracing or triage in overstretched facilities (Fleming et al., 2021). These innovations not only improved real-time response but also laid a foundation for long-term digital health infrastructure **(Table 2)**. Despite these contributions, biomedical engineering was often excluded from formal decision-making processes, highlighting a gap in recognition and integration at the policy level. Many engineers worked behind the scenes without adequate institutional support or professional development opportunities (Agu et al., 2021). This calls for greater inclusion of BMEs in national health emergency planning and sustained investment in their training and deployment across healthcare systems.

Table 2: Role of Biomedical Engineers During the COVID-19 Crisis

Function	Activities	Examples
Equipment Development	Rapid prototyping, local manufacturing	Ventilators, oxygen concentrators, PPE
Maintenance & Adaptation	Repair, calibration, and repurposing	Extending the life of existing equipment, adapting to local settings
Digital Tools Support	Telemedicine, remote monitoring	mHealth applications, sensor networks
Training & Education	Clinical staff instruction	Safe device operation, troubleshooting
Innovation	Frugal engineering solutions	Low-cost, resource-appropriate technology

IV. Regulatory Frameworks and Medical Device Classification

The COVID-19 pandemic revealed critical gaps in the global regulation and classification of medical equipment. Countries faced significant challenges in streamlining the approval, procurement, and deployment of essential devices, particularly as novel solutions involving AI and machine learning emerged to meet urgent healthcare demands.

During the crisis, regulatory bodies in various countries, such as the U.S. Food and Drug Administration (FDA) and the UK's Medicines and Healthcare products Regulatory Agency (MHRA), adopted expedited approval pathways. Emergency Use Authorizations (EUAs) allowed for the temporary deployment of ventilators, diagnostic kits, and digital health solutions, including AI-based triage systems (Muehlematter et al., 2021). However, while these flexible frameworks accelerated innovation, they also raised concerns about long-term device safety, post-market surveillance, and data quality.

Traditionally, the classification of medical equipment is based on the potential risk associated with its use. Regulatory bodies employ tiered systems that range from low-risk (Class I) to high-risk (Class III) devices. However, AI/ML-based medical technologies posed particular challenges for regulators. Their inherent adaptability means that devices can evolve based on real-world data, making traditional static approval models inadequate (Li et al., 2021). Many of these systems are dynamic, meaning they can learn and evolve after deployment, creating a regulatory gray area. Conventional evaluation models assume static devices with fixed performance characteristics, which may not apply to adaptive algorithms (Topol, 2019).

In response to these challenges, agencies began proposing new guidelines for adaptive algorithms. For instance, the FDA introduced a proposed regulatory framework for modifications to AI/ML-based Software as a Medical Device (SaMD), which would allow certain pre-approved changes to occur post-deployment, provided there is robust quality assurance and performance monitoring. Such approaches aim to strike a balance between innovation and patient protection.

In many low- and middle-income countries (LMICs), regulatory fragmentation and limited capacity compounded the crisis. A lack of harmonized classification systems meant that donated equipment often arrived without proper documentation or failed to meet national safety standards (Culkin et al., 2023). Furthermore, inconsistent enforcement of international guidelines, such as those set by the World Health Organization (WHO), hindered equitable access to safe and effective devices (WHO, 2021).

To address these disparities, initiatives such as the Global Harmonization Task Force and the African Medical Devices Forum have emphasized the need for globally aligned classification systems, clearer labeling protocols, and shared databases for device performance and recalls (Kieny et al., 2017). These efforts are especially critical as health systems increasingly adopt connected technologies that cross national boundaries.

V. Digital Procurement and AI/ML Integration in Healthcare Systems

The shift toward centralized digital procurement systems was among the most impactful changes during the pandemic. These platforms enabled real-time tracking of medical devices, optimized distribution logistics, and improved communication between healthcare providers, suppliers, and regulators. In Europe, the MEDICOM platform served as a model, facilitating transparent procurement through standard data formats like XML to ensure interoperability between institutions (Palamas et al., 2001; Chituc, 2017). Countries such as Indonesia adopted mobile-based platforms like Med Market, tailored for doctors and biomedical staff, enabling efficient ordering and stock monitoring. These platforms were developed using active methodologies such as Lean Startup principles, allowing for iterative updates based on user feedback (Prihandono et al., 2024; Bortolini et al., 2021).

AI and ML emerged as transformative tools during the COVID-19 pandemic, with biomedical engineers playing a critical role in their deployment. These technologies were rapidly adapted to address pressing needs in diagnostics, epidemiological modeling, and decision support across healthcare systems (Naudé, 2020; Bullock et al., 2020).

One of the most prominent applications was the use of ML algorithms for early and rapid detection of COVID-19 through imaging modalities such as chest X-rays and CT scans. Biomedical engineers collaborated with clinicians and data scientists to develop and refine diagnostic tools capable of distinguishing COVID-19 from other respiratory conditions with high sensitivity and specificity (Shi et al., 2020). These AI-enabled systems helped reduce diagnostic delays, especially in settings where trained radiologists were scarce.

Beyond diagnostics, ML models were used to predict the spread of the virus, estimate resource needs, and optimize hospital capacity. Predictive models guided public health interventions by forecasting infection peaks, identifying high-risk populations, and informing lockdown or resource allocation strategies (Arora et al., 2020). AI also supported decision-making in ICUs, helping triage patients based on disease severity, assisting in ventilator allocation, and monitoring patient deterioration in real-time (Naudé, 2020). Despite these advancements, concerns around algorithm bias, data privacy, and regulatory oversight persisted. Many AI/ML models were trained on limited or non-representative datasets, raising concerns about generalizability across different populations. Biomedical engineers advocated for rigorous model validation, transparency in algorithm development, and ethical frameworks to guide deployment (Bullock et al., 2020).

VI. The Digital Transformation of Healthcare

The healthcare industry is undergoing a profound digital transformation, increasingly influenced by platform-based ecosystems that reshape how value is created and delivered. Traditional healthcare systems primarily operated within tightly managed institutional or supply chain boundaries. However, digital platforms, by leveraging two-sided market models and broader interorganizational collaboration, enable value co-creation with a diverse array of stakeholders, including startups, tech firms, patients, and service providers.

Despite the widespread adoption of platform ecosystems in sectors such as finance, retail, and transportation, both academic research and real-world implementation in the healthcare sector have remained relatively slow. Hermes et al. (2020) addressed this gap by analyzing data from 1,830 healthcare organizations listed on Crunchbase to identify how value is orchestrated across a new digital healthcare landscape. Their study mapped a generic ecosystem comprising eight emerging roles: (1) information platforms, (2) data collection technologies, (3) market intermediaries, (4) remote and on-demand health services, (5) augmented and virtual reality providers, (6) blockchain-enabled personal health record (PHR) systems, (7) cloud service providers, and (8) intelligent data analytics platforms. These actors fundamentally redefine how healthcare value propositions are formed and delivered **(Figure 1)**.

Digital platforms have also redefined the way clinical trials are conducted by overcoming long-standing logistical challenges such as participant recruitment, cost management, and scalability. With the advent of mHealth tools and digital communication technologies, "remote trials" now offer a promising, cost-effective alternative (Dahne et al., 2020). These trials are centrally coordinated but remotely executed, which allows for faster recruitment of diverse and representative participant samples across communities, states, or even countries.

The global proliferation of mobile applications for health management in both preventive and clinical contexts has allowed emerging markets to leapfrog traditional infrastructure limitations. According to Alanezi and Alanzi (2020), the expansion of the gig economy and mobile-based service models has enabled flexible, short-term health service engagements, a trend that aligns with the digital consumer mindset and further decentralizes care delivery.

Fig. 1. Emerging Digital Healthcare Ecosystem Roles.

VII. Evolution of Digital Procurement Systems in Healthcare

The procurement landscape in healthcare is being redefined by digital transformation. Historically rooted in basic e-procurement tools developed in the 1990s, procurement systems have now evolved to incorporate advanced technologies such as artificial intelligence, blockchain, and predictive analytics. These technologies support real-time risk monitoring, cost optimization, and vendor transparency, key factors in modern healthcare supply chain management (Herold et al., 2021; BCG, 2018) **(Figure 2)**.

Today, over 4,000 digital procurement platforms exist globally, generating more than $6 billion in annual revenue and are projected to grow at a rate of 10.2% annually until 2026. Despite this surge, adoption remains uneven. Research by the Fraunhofer Institute indicates that only 28% of surveyed companies actively use these advanced tools in procurement. Barriers include limited awareness, unclear strategic frameworks, and skepticism regarding long-term value (Herold et al., 2021). To provide a more grounded understanding of this transition, Herold et al. (2021) applied the Dynamic Capabilities Theory (DCT) to explore how Chief Procurement Officers (CPOs) can drive digital transformation. Their findings emphasize that procurement innovation should not be viewed merely as a functional upgrade but as a strategic overhaul that requires leadership alignment, workforce training, and cultural change.

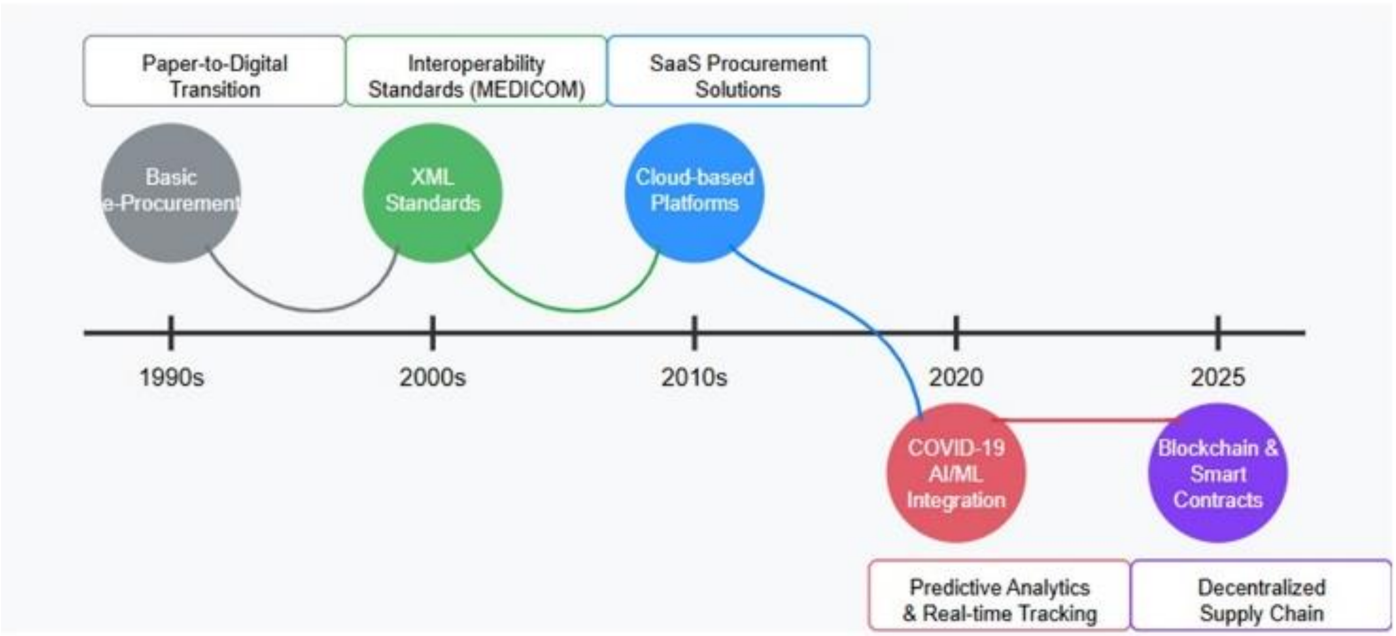

Fig. 2. Timeline showing the Evolution of Digital Procurement Systems in Healthcare. *SaaS abbreviation stands for "Software as a Service".

VIII. Strengthening Healthcare Infrastructure Through Smart Procurement

Pharmaceutical corruption remains a serious global health challenge. Each year, an estimated $7.5 trillion is spent globally on health services. Yet, up to 6%, approximately $300 billion, is lost to corruption and errors. In developed countries alone, the cost of corruption is estimated at $12 to $23 billion annually. It is estimated that 10% to 30% of public procurement spending is lost to mismanagement and corruption. This risk also extends to the complex and global ecosystem of pharmaceutical procurement, where corruption can directly impact patient and population health by limiting equitable, safe, and affordable access to medicines (Mackey & Cuomo, 2020).

The World Health Organization (WHO) defines access to medicines as "having medicines continuously available and affordable at public or private health facilities," which includes access to all health products and medical devices. This concept is supported by a framework focused on rational selection, affordable pricing, sustainable financing, and reliable health and supply systems (Yenet et al., 2023). Importantly, global health stakeholders are now addressing pharmaceutical corruption through anti-corruption initiatives. In February 2019, an international coalition established the Global Network on Anti-Corruption, Transparency, and Accountability (ACTA). These efforts are crucial because corruption in pharmaceutical procurement undermines all four pillars of the WHO's access framework. Group Purchasing Organizations (GPOs) play a central role in the healthcare supply chain by enabling cost savings, volume discounts, and strategic vendor selection. However, traditional GPO contract processes are often time-consuming and inefficient. To address this, blockchain-based solutions integrating smart contracts and decentralized storage have been proposed. Using the Ethereum blockchain, such solutions link all major stakeholders, manufacturers, GPOs, distributors, and providers. A smart contract framework automates the GPO contract process and is supported by detailed algorithms mapping stakeholder interactions (Omar et al., 2021).

IX. Global Health Equity and Technology Access

The COVID-19 pandemic underscored longstanding global inequities in healthcare access, infrastructure, and technology. Low- and middle-income countries (LMICs), in particular, faced compounded challenges due to limited health system capacity, unequal vaccine distribution, and scarce access to life-saving technologies. Biomedical engineers have a crucial role to play in addressing these disparities through context-appropriate innovations and advocacy for equitable technology distribution.

Access to essential medical equipment, such as ventilators, infusion pumps, and diagnostic devices, was highly unequal across regions. While high-income countries rapidly expanded production and procurement channels, LMICs often relied on donated or surplus equipment that was sometimes incompatible with local infrastructure or lacked appropriate training and maintenance support. Biomedical engineers in these settings often had to adapt or modify donated technologies to ensure functionality in different power conditions, environmental constraints, or clinical workflows (Malkin, 2007).

Global disparities in oxygen availability emerged as a defining inequity during the pandemic. Many hospitals in low-resource settings lacked access to centralized oxygen systems or reliable cylinder supply chains. In response, biomedical engineers contributed to the design and implementation of locally manufactured oxygen concentrators, pressure swing adsorption plants, and solar-powered delivery systems. These interventions exemplify the value of frugal innovation, creating affordable, reliable technologies specifically suited to the realities of under-resourced environments (Howitt et al., 2012).

Digital health disparities also became apparent. Countries with well-established telemedicine infrastructure, EHRs, and AI-driven tools were better positioned to maintain care continuity and pandemic surveillance. In contrast, many LMICs lacked the infrastructure for even basic digital health interventions. Biomedical engineers supported the development and deployment of open-source or low-bandwidth digital tools to support triage, remote consultations, and data collection in areas with limited internet access.

Equity also concerns representation and inclusion in the design and deployment of medical technologies. Most devices are developed with assumptions about resource availability, end-user expertise, and environmental conditions that do not reflect the global majority's realities. Biomedical engineers, particularly those working in or with LMICs, are advocating for inclusive design processes that involve local stakeholders in every stage of the innovation pipeline, from needs assessment to post-market surveillance (Harris et al., 2021).

X. Future Directions and Post-Pandemic Strategies

The pandemic has accelerated the digital transformation of healthcare, but sustaining these advances requires long-term investment, interdisciplinary collaboration, and thoughtful regulation. One priority is the development of resilient and scalable digital procurement systems that integrate real-time inventory tracking, demand forecasting, and supplier coordination. These platforms should adhere to global interoperability standards and enable hospitals to respond dynamically to future surges in demand (Palamas et al., 2001; Chituc, 2017). Another future focus should be the formal integration of biomedical engineers into hospital leadership and emergency preparedness teams. Their cross-disciplinary expertise makes them uniquely qualified to lead medical technology planning, ensure infrastructure readiness, and maintain compliance with safety standards (Omotayo Adelodun, Chinyere Anyanwu, et al., 2024).

Policy reform is also needed to keep pace with the evolving role of AI/ML. Regulators must create transparent, risk-based pathways for AI/ML devices, with clear criteria for approval, auditing, and post-market surveillance. In addition, frameworks that promote explainability and user control will help clinicians and patients build trust in these systems. Importantly, AI systems should complement, not replace, human judgment. Educational programs for biomedical engineers, clinicians, and IT staff should also evolve to include digital literacy, AI ethics, and procurement technology. Building institutional capacity around these competencies will ensure that health systems are not only reactive to crises but also proactive in adopting and governing innovation.

XI. Conclusion

The COVID-19 pandemic was a catalyst for reimagining how healthcare systems utilize technology. Biomedical engineers played a vital role in responding to this crisis, ensuring that critical equipment was maintained, deployed, and innovated under immense pressure. At the same time, digital procurement systems and AI/ML tools offered unprecedented opportunities for improving care delivery and resource management. However, these gains revealed gaps in regulatory preparedness, infrastructure interoperability, and clinical adoption frameworks. Going forward, building a resilient and adaptive healthcare system will depend on integrating engineering expertise, data science, and human-centered design. With appropriate investment, policy reform, and interdisciplinary collaboration, healthcare technology can be transformed into a strategic asset for both routine care and emergency preparedness.

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Not Applicable

Consent for publication

Not Applicable

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Not Applicable

Competing interests

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