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Research Article

Serialization Systems: Advancing Pharmaceutical Equity and Pandemic Preparedness in Global Healthcare

Sasikiran Karanam*

University at Albany - State University of New York, USA
* **Corresponding Author Email:** kirankkaranam@gmail.com - **ORCID:** 0000-0002-9947-7850

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Abstract:

The COVID-19 outbreak demonstrated the existence of fatal weaknesses in world pharmaceutical supply chains, unveiled the existence of far-reaching disparities in medicine and vaccine distribution between developed and developing countries. Serialization systems-technological tools that unite pharmaceutical products with distinctive identifiers become central in the way to mitigate healthcare disparities to improve pandemic preparedness. This pandemic revealed that the disjointed distribution channels, vaccine nationalism, and insufficient tracking infrastructure systematically marginalized vulnerable groups, leaving gaps in vaccination coverage that were sustained across pivotal periods of disease spread. There was the development of counterfeited pharmaceuticals during the crisis, which was especially high in areas where regulation was poor, leading to preventable deaths and eroding confidence in healthcare systems. The integration of blockchain technology, the Internet of Things, and digital health platforms presents promising opportunities to improve pharmaceutical traceability, and the pilot implementations of the technologies result in significant decreases in the rate of counterfeit drug penetration and the effectiveness of the supply chain. But there are serious obstacles to the implementation of serialization in resource-constrained environments, such as poor infrastructure, prohibitive costs of implementation, and large digital divides that threaten to contribute to any existing health inequities. Smaller pharmaceutical companies have a greater challenge than larger multinational corporations, which begs the question of how this may affect the affordability and accessibility of medicine in the low income markets. Implementing strategic plans should be done with attention to the accessibility, interoperability, and capacity building to ensure that serialization systems do not advance equity purposes, but instead, strengthen the gaps. The mechanisms of international cooperation, collaboration between the government and industry, and technological transfer can be critical in creating the infrastructure of a sustainable serialization that will be able to provide the routine distribution of pharmaceutical products and react quickly to an emergency situation in the future.

1. Introduction

The transportation of life-saving drugs across continents and through the hands of thousands of people forms one of the most confounded chains of the contemporary business. This pharmaceutical supply chain supports billions of lives, but geography, economics, and changing regulations make the process of getting drugs to the patient a constant complication. Serialization, that is, assigning a distinct identifier to each pharmaceutical product, began as an easy way to identify counterfeit medicines. Gradually, however, this method became much larger, affecting not only the issue of healthcare equity but also the preparedness for health-related disasters on the international level.

COVID-19 crashed upon pharmaceutical supply chains like a freight train. The harm created uncomfortable distances between the way the wealthy and impoverished countries reached the vaccines and treatment. In the US alone, the deployment brought to light bitter rifts that were along racial and economic lines. In those initial, critical months, Hispanic and non-Hispanic Black populations were approximately 30-40 years behind

the Whites in vaccination rates. Uninsured individuals? Even worse, trailing by nearly 25% compared to those with comprehensive health coverage [1]. Outside American borders, the picture looked equally bleak. Wealthy countries grabbed disproportionate vaccine shares through advance purchase deals, leaving poorer nations to scrape together whatever remained. Distribution happened in fragments, with federal, state, and local authorities making separate decisions without any unified tracking. The scattered approach significantly impacts vulnerable groups, delaying vaccine access by 3 to 4 weeks compared to affluent neighborhoods [1]. Distance posed another obstacle. The rural inhabitants exceeded a distance of 15-20 miles compared to the city dwellers, only to locate vaccination points, which posed a significant obstacle to the aged and those who had no reliable means of transportation [1].

COVAX was made a multilateral alternative which would offer equity in dispensing vaccines to 92 low- and middle-income countries. The project was supported by quite ambitious objectives: by the end of 2021, 20 percent of the population of the countries participating in it was to be vaccinated. Reality delivered something else entirely. Only 12% of the projected 2 billion doses actually reached their destinations during that window [2]. Budgetary troubles plagued COVAX from the start. The initiative faced a funding gap topping $16.8 billion throughout 2021, crippling procurement power and forcing dependence on unreliable donated doses instead of solid purchase agreements [2]. Rich nations hoarding vaccines made everything harder. Bilateral deals secured roughly 7 billion doses for high-income countries by mid-2021—amounts exceeding actual population needs by massive margins—while COVAX fought for leftover manufacturing capacity [2]. Logistics added another layer of problems. mRNA vaccines needing storage at -70°C created impossible situations in countries lacking proper infrastructure. Vaccine wastage rates hit 15-20% in some resource-starved settings, while well-equipped systems kept losses under 2% [2]. The takeaway became crystal clear: equitable distribution remains a fantasy without solid traceability systems monitoring vaccine movement from production to the patient. Weak populations continue to be disadvantaged during critical periods of the pandemic.

2. Disparities in Pharmaceutical access in the world, with the example of the COVID-19 pandemic.

Having become a pandemic, academic debates on the subject of healthcare equity became a question of life and death to millions of people around the globe. COVAX, designed as an international cooperation's shining example, instead became a lesson in how global health governance crumbles under pressure. Despite targeting 92 low- and middle-income countries, the program stumbled badly, with delays and shortfalls wrecking its central purpose [3]. Problems piled up from multiple directions. Donor nations held back adequate financial support, creating chronic underfunding that strangled procurement efforts and forced reliance on unpredictable donations rather than stable purchase contracts [3].

Vaccine nationalism inflicted serious damage. High-income countries signed bilateral contracts, grabbing doses far beyond reasonable needs—often sufficient to vaccinate entire populations three, four, even five times over. This behavior drained global manufacturing capacity, forcing COVAX to battle for scraps of production time [3]. The resulting vaccination gaps were shocking. Mid-2021 saw the United States, United Kingdom, and Israel pushing past 60% population coverage. Meanwhile, most African nations crawled along under 3%. Some countries barely reached 1% even as the Delta variant surged [3]. Cold chain logistics added another crushing weight, especially for mRNA vaccines requiring ultra-cold storage between -60°C and -80°C. Infrastructure for maintaining such conditions simply didn't exist across resource-limited settings, where basic refrigeration already fell short of vaccine preservation needs [3].

The inequity in vaccines was a half story. During the pandemic, counterfeit drugs burst into flames and hit the vulnerable groups the most. Investigations across developing country markets uncovered disturbing realities. Fake drugs made up 10-30% of medicines available in low- and middle-income nations—dramatically outpacing the roughly 1% rate found in high-income countries with strong regulatory teeth [4]. The economics were mind-boggling: the counterfeit drug trade hit approximately $200 billion per year, capturing 10-15% of the entire worldwide pharmaceutical market. Africa, Asia, and Latin America took the worst hits, with weak regulatory enforcement creating perfect conditions for criminals [4].

Counterfeiters played the pandemic desperation brilliantly, flooding markets with bogus products claiming to prevent or cure COVID-19. Fake vaccines, phony hydroxychloroquine, forged remdesivir, worthless diagnostic tests giving wrong results—desperate populations bought it all [4]. Sub-Saharan Africa saw especially brazen fraud

around antimalarial drugs, which criminals falsely marketed as COVID-19 treatments without any clinical backing. Counterfeiting rates for these medications topped 35%. Some contained zero active pharmaceutical ingredients. Others packed dangerous substitutes: industrial chemicals, heavy metal contaminants [4].

The death toll was horrifying. Conservative estimates placed preventable deaths from counterfeit antimalarial drugs alone between 72,000 and 267,000 annually across sub-Saharan Africa. These deaths stemmed from treatment failures when patients unknowingly swallowed ineffective fakes instead of real medicines [4]. Those numbers excluded deaths from counterfeit antibiotics, heart medications, and cancer drugs. The actual human cost of pharmaceutical counterfeiting probably dwarfs official estimates, possibly representing the most underrecognized public health disaster facing vulnerable populations worldwide [4].

3. Serialization as Infrastructure for Pharmaceutical Equity and Authenticity

Tackling fundamental problems in pharmaceutical supply chains demands technological answers. Serialization systems provide exactly that, with special power for addressing medicine distribution unfairness and fighting counterfeit products. The basic idea sounds simple: stick unique identifiers—usually two-dimensional data matrix codes—onto individual pharmaceutical packages. These markers enable tracking and tracing throughout the entire supply chain, from the manufacturing plant to the patient's hand. Simple concept, massive implications when rolled out strategically with proper verification tools.

Counterfeiting ranks among pharmaceutical safety's nastiest threats across developing regions. Rough estimates put counterfeit medicines at 10-30% of pharmaceutical products throughout many low- and middle-income countries, fueling treatment failures, drug resistance, and deaths that shouldn't happen. Blockchain technology burst onto the scene as a potential game-changer for pharmaceutical supply chain security. The technology provides unalterable, decentralized ledger systems that generate unaltered records of all the transactions, starting with the manufacturing process, to the distribution and dispensing of the final product.

A single systematic review explored the use of blockchain in the pharmaceutical sector, reviewing 52 peer-reviewed papers that were published between 2016 and 2021. The results jumped off the page. Blockchain-based serialization systems hit counterfeit detection accuracy rates of 98.7%, crushing conventional track-and-trace systems that typically caught only 65-72% of fraudulent products trying to sneak into legitimate supply chains [5]. The technology's distributed setup worked especially well in developing markets. Pilot programs across pharmaceutical supply chains in Nigeria, Kenya, and Ghana showed a 67% drop in counterfeit drug penetration within just 18 months of blockchain rollout. That translates to roughly 8,400 prevented deaths per year across those three countries [5].

Money-wise, the numbers made sense. Blockchain implementation for national-scale pharmaceutical traceability systems ran about $2.3 million in costs but generated estimated gains of $47-52 million annually. Those gains flowed from multiple streams: fewer counterfeit-related healthcare expenses, reduced treatment failures requiring costly backup therapies, and tighter supply chain efficiency, slashing inventory carrying costs by 23-28% [5]. The war on counterfeits was but a prologue. Supply chain transparency was unlocked on a scale that had never happened before. Smart contracts automatically fired off alerts when medications neared expiration dates or suffered temperature problems during transport. Pilot programs cut pharmaceutical waste by 31% while guaranteeing medicines reaching patients kept their full therapeutic punch [5]. Cross-border pharmaceutical trade gained particular advantages from the technology's interoperability features, letting serialization data flow smoothly between different national regulatory systems without needing centralized international databases, raising data sovereignty headaches. This capability greases international medicine distribution during emergencies while keeping security standards tight [5].

Beyond authentication, serialization enhances supply chain transparency in ways that directly support equitable distribution, creating detailed records of medicine movement from manufacturing facilities through distribution networks to dispensing locations. India's implementation of serialization principles during the COVID-19 pandemic through the CoWIN digital platform demonstrates both the transformative potential and persistent challenges of deploying track-and-trace technologies at a population scale in resource-constrained settings. The platform coordinated distribution and administration of over 2 billion vaccine doses between January 2021 and December 2022, representing the world's largest vaccination campaign and demonstrating the technical feasibility of serialization-integrated digital health infrastructure serving populations exceeding 1.4 billion individuals [6]. However, the digital platform approach encountered significant equity

challenges rooted in India's substantial digital divide, where only 54% of the population possessed internet access, and smartphone penetration reached merely 46% of adults during the vaccination campaign's critical phases [6]. Rural populations, particularly elderly individuals and marginalized communities, including tribal groups and urban slum residents, experienced systematic barriers to platform access, with registration requiring Aadhaar identification numbers, active mobile phone numbers, and digital literacy that remained unavailable to approximately 35% of the target vaccination population [6]. These technological barriers translated directly into vaccination disparities, with urban areas achieving 78% coverage by mid-2022 while rural areas reached only 62% coverage, and educated populations with college degrees demonstrating vaccination rates 23 percentage points higher than populations with primary education or less [6]. The platform's mandatory online registration system inadvertently created a two-tier vaccination system wherein digitally connected populations secured appointments rapidly while digitally marginalized groups required assistance from civil society organizations and community health workers to navigate registration processes, delaying their vaccination by an average of 6-8 weeks compared to digitally literate urban residents [6]. These experiences underscore that serialization and digital health infrastructure, while offering powerful capabilities for enhancing pharmaceutical equity, require careful attention to accessibility and inclusion to avoid exacerbating existing health disparities through technological solutions that privilege already-advantaged populations [6].

4. Technological Innovation and Future-Ready Serialization Systems

Emerging technologies offer pathways to enhance serialization system capabilities beyond current implementations, with particular potential to address challenges in resource-limited settings and pandemic-scale deployments. Three areas of future technology include blockchain technology, integration of Internet of Things (IoT), and analytics enhanced by artificial intelligence, which have immense potential to support the traceability and equity of pharmaceuticals.

The blockchain technology offers distributed ledger systems that cannot be tampered with to record the process of supplying pharmaceuticals to the supply chain, and it is offering solutions to the problem that are especially helpful to situations where trust in centralized authorities is still low or corruption threatens the integrity of the supply chain. The adoption of hybrid solutions with blockchain and IoT sensors has shown a potential for revolutionizing the realm of pharmaceutical traceability and taking care of a wide range of issues at once across the entire pharmaceutical supply chain, including manufacturing, distribution, and delivery to patients. Comprehensive study of hybrid blockchain-IoT frameworks in the pharmaceutical industry revealed that integrated systems combining distributed ledger technology with real-time sensor networks achieved authentication success rates of 99.4% for pharmaceutical products throughout multi-tier supply chains, substantially exceeding the 68-74% authentication rates documented in conventional barcode-based tracking systems operating in comparable market conditions [7]. The hybrid architecture's IoT components enabled continuous environmental monitoring, with temperature sensors recording data at 10-minute intervals and humidity sensors capturing readings every 15 minutes throughout transport and storage phases, generating approximately 8,640 environmental data points per pharmaceutical shipment during typical 30-day distribution cycles from manufacturer to pharmacy [7]. Pilot implementations across supply chains serving India, Bangladesh, and Sri Lanka, encompassing approximately 3.2 million pharmaceutical packages tracked over 24-month evaluation periods, documented that the blockchain-IoT system reduced counterfeit drug infiltration by 81% compared to baseline measurements using traditional paper-based documentation, while simultaneously decreasing temperature-related product degradation by 54% through early detection capabilities that enabled corrective interventions before irreversible pharmaceutical damage occurred [7]. The system's smart contract functionality automated compliance verification processes, reducing regulatory inspection time from an average of 6.5 hours per pharmaceutical consignment to approximately 18 minutes while simultaneously improving compliance documentation accuracy from 73% to 97%, thereby accelerating legitimate pharmaceutical distribution while strengthening regulatory oversight [7]. Economic analysis demonstrated favorable cost-benefit ratios even in resource-constrained environments, with implementation expenses averaging $4.2 million for national-scale deployments across countries with populations of 50-100 million generating estimated annual benefits of $32-41 million through reduced counterfeit-related healthcare expenditures, decreased pharmaceutical waste, improved supply chain efficiency that reduced distribution costs by 19-23%, and enhanced patient safety outcomes that

prevented an estimated 12,000-15,000 adverse drug events annually in pilot implementation regions [7]. These technological capabilities proved especially valuable during pandemic response scenarios, where the system's real-time tracking enabled health authorities to monitor vaccine distribution with unprecedented granularity, identifying bottlenecks within 2-3 hours compared to 48-72 hours typical of conventional reporting systems, thereby enabling rapid reallocation of resources to underserved areas experiencing distribution delays [7].

However, technological innovation alone cannot address systemic challenges in pharmaceutical equity, as advanced serialization technologies require supporting infrastructure that remains limited in many low-resource settings. Examination of blockchain-based pharmaceutical traceability implementation across diverse healthcare systems revealed substantial disparities in technological readiness, with critical infrastructure deficiencies constraining adoption in precisely those regions where counterfeit pharmaceuticals posed the most severe public health threats. Analysis of blockchain deployment requirements for pharmaceutical supply chain security documented that effective implementation necessitated consistent electricity availability for at least 20 hours daily, internet connectivity with a minimum sustained bandwidth of 5 Mbps, and trained technical personnel capable of system configuration, maintenance, and troubleshooting [8]. Infrastructure assessments across 47 low- and lower-middle-income countries revealed that these prerequisites remained unavailable in approximately 52% of district-level health facilities and 68% of rural health centers, creating substantial barriers to implementing advanced serialization technologies in regions experiencing counterfeit drug prevalence rates of 25-40% [8]. Energy infrastructure emerged as the most critical constraint, with field studies documenting that 71% of rural healthcare facilities in sub-Saharan Africa and 58% in South Asia experienced power interruptions averaging 6-10 hours daily, requiring expensive solar power systems or diesel generators that increased implementation costs by 42-55% while adding ongoing fuel and maintenance expenses averaging $8,000-12,000 annually per facility [8]. Telecommunications infrastructure posed additional challenges, with mobile network coverage proving inadequate in 39% of rural areas across surveyed countries, and where coverage existed, connection reliability fell below system requirements 23-31% of operating hours due to network congestion or equipment failures [8]. Human capacity constraints compounded technological barriers, with workforce assessments revealing that only 18% of healthcare workers in rural facilities possessed digital literacy sufficient to operate blockchain-based systems without extensive training, and training programs requiring 50-70 hours per worker proved difficult to implement given chronic staff shortages that left facilities unable to release personnel for extended training periods [8]. These infrastructure and capacity gaps underscore risks that sophisticated serialization technologies could inadvertently deepen existing health inequities by creating "serialization divides" wherein well-resourced urban facilities implement advanced tracking while rural facilities serving the most vulnerable populations continue relying on paper-based systems offering minimal counterfeit protection [8].

5. Implementation Challenges and Strategic Considerations

Regardless of the strong theoretical advantages, the utilization of serialization is faced with significant practical challenges, especially in developing countries, which are the ones that would benefit the most due to the improved traceability of pharmaceuticals. The awareness of these issues is critical to devising implementation policies that can meet the equity goal and not unintentionally support the existing disparities.

Most of the low- and middle-income countries have infrastructure constraints as the most obvious impediments to adopting serialization, as serialization requires stable, dependable electricity to scan equipment and transfer data, steady internet connectivity to make real-time verifications, and digital literacy among the supply chain players. Evaluation of substandard and falsified medical product notifications in a variety of regulatory settings demonstrated systematic patterns of how infrastructure inadequacies facilitated the spread of counterfeit drugs, and at the same time, limited the measures to enforce technological solutions to curb the issue. Examination of 1,500 notifications of substandard and falsified medical products reported to WHO between 2013 and 2017 documented that 42% of incidents occurred in regions of Africa, 21% in regions of the Americas, and 20% in Southeast Asian regions, geographic distributions correlating strongly with infrastructure limitations that prevented effective pharmaceutical authentication systems [9]. Antimalarials were by far the most commonly reported category of substandard and falsified products (19.6 of all notifications), followed by antibiotics (16.9%) and anesthetics (8.5), and these types of therapeutic products had by far the most severe impact of counterfeit introduction because of their life-saving

status and high demand in the resource-constrained environment [9]. The results of the analysis of the sources of notification have shown that 39 percent of reports were by regulatory authorities of the member states, 25 percent by regional or sub-regional organizations and 19 percent by WHO surveillance systems, which implies that underreporting was high in those regions with insufficient pharmacovigilance infrastructures, where the actual prevalence of counterfeits might have been 3-5 times higher than reported cases [9]. Geographic analysis showed that countries of the WHO African and South-East Asian regions reported 64 percent of all notifications in substandard and falsified products even when they only contributed 37 percent of overall pharmaceutical consumption in the world, and this showed how the gaps in infrastructure in these areas left the regions susceptible to counterfeit infiltration which could be overcome with implementation barriers with removal possible with a serialization system [9]. Economic impact measures revealed that the annual economic losses caused by substandard and counterfeited medical products were in the range of 10-25 billion worldwide, and the economic costs were directly brought about by the direct healthcare expenditures, lack of productivity due to failure to treat, and the loss of public confidence in the healthcare systems [9]. These statistics highlight the role of inadequate infrastructure as the cause of vicious cycles, where the most severely impacted regions in counterfeit pharmaceuticals suffer the most in terms of implementing serialization technologies that have the potential to reduce the issue [9].

Resistance to change emerges as a significant human dimension of implementation challenges, compounding technical and financial barriers to serialization adoption. The analysis of the experiences of pharmaceutical serialization implementation in different organizational environments showed that small manufacturers have a disproportionately high number of difficulties in comparison with other large multinational corporations that have more resources and technical capabilities. The serialization compliance studies of pharmaceutical manufacturers have reported that the implementation cost differs radically depending on the size and complexity of the organization with the small manufacturers (under 50 stock keeping units or SKUs) incurring average implementation costs of serialization in terms of cash expenditure and time (implementation) of approximately 150,000-200,000 and the medium manufacturers of between 50-200 SKUs recording costs of 300,000-450,000 and the large manufacturer of over 200. These capital requirements represented substantially different proportions of organizational capacity, with serialization costs consuming 15-25% of annual capital expenditure budgets for small manufacturers compared to only 3-8% for large pharmaceutical companies with diversified revenue streams and greater financial flexibility [10]. Technical complexity proved equally challenging, with assessments revealing that serialization integration required modifications to 60-85% of existing packaging lines in small manufacturing facilities compared to 35-50% in large facilities with newer equipment designed with serialization capabilities, creating substantial downtime and production losses during implementation periods [10]. Small manufacturers reported implementation timelines averaging 18-24 months from initial planning through full deployment compared to 12-16 months for large manufacturers with dedicated technical teams and established project management capabilities [10]. Workforce training emerged as a critical bottleneck, with small manufacturers averaging only 2-4 quality assurance personnel responsible for overseeing serialization implementation compared to dedicated teams of 15-30 specialists in large organizations, resulting in substantially higher per-employee workload and implementation stress [10]. Regulatory compliance challenges compounded these difficulties, with small manufacturers exporting to multiple markets facing requirements to implement divergent serialization schemes for different destination countries, creating quality control challenges wherein serialization-related deviations occurred at rates of 8-12 incidents per million packages in small facilities compared to 2-4 per million in large facilities with sophisticated quality management systems and automated verification processes [10]. These disparities underscore risks that serialization mandates, while advancing important public health objectives, could inadvertently disadvantage small manufacturers serving low-income markets, potentially reducing pharmaceutical access and competition in precisely those settings where generic medicines from small producers play essential roles in ensuring affordable access to essential treatments [10].

Table 1: *Vaccine Distribution Barriers in U.S. and Global Settings [1,2]*

Population Group	Access Challenge	Impact Severity
Racial minorities	Lower vaccination priority	Substantial delay
Uninsured individuals	Limited healthcare access	Significant gap

Rural communities	Distance to facilities	Major barrier
Low-income countries	Funding shortfalls	Critical shortage
COVAX recipients	Donation dependency	Unreliable supply

Table 2: *Counterfeit Pharmaceutical Crisis Across Economic Contexts [3,4]*

Region	Counterfeit Prevalence	Regulatory Strength
High-income nations	Minimal presence	Strong oversight
Sub-Saharan Africa	Widespread problem	Weak enforcement
Southeast Asia	Significant threat	Variable capacity
Latin America	Moderate-high	Inconsistent
Antimalarial drugs	Extreme vulnerability	Life-threatening

Table 3: *Blockchain Serialization vs. Digital Platform Implementation [5,6]*

System Feature	Blockchain Technology	Digital Platforms
Authentication accuracy	Highly effective	Platform-dependent
Infrastructure needs	Moderate requirements	Extensive connectivity
Equity impact	Reduces counterfeits	Creates a digital divide
Cost-benefit	Strong returns	Variable outcomes
Accessibility	Technical barriers	Literacy barriers

Table 4: *Hybrid Technology Systems and Infrastructure Readiness [7,8]*

Implementation Factor	Advanced Systems	Resource-Limited Settings
Technology sophistication	Cutting-edge integration	Basic requirements
Power availability	Continuous needed	Frequent interruptions
Network connectivity	High-speed essential	Often inadequate
Personnel training	Specialized skills	Limited capacity
Deployment success	Urban facilities	Rural challenges

6. Conclusions

Pharmaceutical serialization is the disruptive infrastructure to solve the problems of healthcare inequity and improve the preparedness to pandemics, but the achievement of this opportunity is fraught with complex technical, financial, and social issues. The COVID-19 pandemic has shown, beyond doubt, that the vulnerabilities of the pharmaceutical supply chain are being directly converted into avoidable loss of life and increased suffering, especially in those who are already marginalized. The benefits of high-income countries, the lack of multilateral coordination systems, and non-existent comprehensive tracking systems conspired to introduce inequities in vaccination, whereby privileged groups received immunity months before vulnerable groups started experiencing greater disease burden due to their exposure. The fake drugs went on the rise because of regulatory loopholes and supply chain fragmentation, leading to treatment failure and loss of trust in the healthcare facilities when trust was most needed. Serialization technologies provide the means to counterfeit with potent tools to enhance supply chain transparency, improve equitable resource distribution, and even have demonstrated remarkable precision in counterfeit detection and significant returns on investment despite resource constraints, even in resource-limited environments. Digital health services that apply principles of serialization can help organize greater distribution of pharmaceuticals, which a massive vaccination campaign in India, during which more than one billion people were vaccinated, exemplified. Nevertheless, endemic digital disparities, infrastructure shortages, and capacity restrictions limit the adoption of serialization in those areas where counterfeitation is most prevalent and health demands the most. The load of implementation placed on small pharmaceutical manufacturers is disproportionate to that of large corporations, which leads to the concern of any possible effects on the affordability of medicine and generic competition in low-income markets. Effective serialization requires deliberate design decisions that focus on access, such as offline verification with training programs that are culturally relevant and technology transfer that develops sustainable local capacity instead of developing external dependencies. To make interoperability work, international organizations need to reconcile the standards of serialization with the justifiable regulatory diversity, which will permit the distribution of medicine across national borders, and in case of an emergency. The mobilization of

resources to develop infrastructure and technical assistance can be accomplished with the help of the public-private partnership, but it is necessary to govern the process carefully to balance the commercial interests with the needs of the population's health. Capacity building programs that cover regulatory, supply chain staff, healthcare, and patients are initial investments in which technological systems cannot realize their equity potential. The way ahead would be a long-term investment on the side of various stakeholders to achieve the same objectives of universal health coverage and pandemic preparedness. Serialization on its own is not the answer to structural inequities that determine what is possible in global health, but when strategically applied as a component in wholesome health systems fortification, they can play a positive role in developing healthcare infrastructure that is devoted to all populations in the pursuit of safety, quality, and dignity. The first call to action is clear: pandemic preparedness in the future requires a structure of serialization that can be activated quickly in case of an emergency, pre-positioned capacity such as trained staff and well-established governance channels, and cross-border distribution mechanisms that can quickly and effectively distribute across borders while ensuring traceability. The investment in fair serialization systems is not only a technical innovation but also a matter of basic adherence to the idea that healthcare is a universal human right and not a privilege based on geography or money.

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