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Epidemiological Fallout from Immunization Program Interruptions

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Abstract

Disruptions in routine immunization programs can undermine population immunity and lead to outbreaks of vaccine-preventable diseases (VPDs). In addition to the direct threat posed by COVID-19, operational and logistical challenges, disruption of supply chains, and the effect of COVID-19 on the health system, health workforce, and disease surveillance can hinder vaccination and leave children unprotected against diseases such as measles, polio, and yellow fever. Monitoring vaccination coverage, adaptation of immunization activities, and strengthening sentinel surveillance can facilitate early detection of VPD outbreaks. Recovery in routine immunization programs requires not only the resumption of normal health service delivery but also catch-up campaigns, improvement in supply chains, and intensive engagement with affected communities.

Vaccination coverage is usually monitored on the basis of reported national administrative data but without formal validation, which compromises confidence in estimates of the actual number of children vaccinated, especially during wartime or severe epidemics. Coverage has fallen in many countries. Despite recommended herd immunity thresholds of at least 95%, suboptimal immunity may persist in areas with low vaccination coverage. Even in countries where high coverage is achieved at the national level, pockets of low uptake can facilitate the spread of VPDs.

Keywords : Routine immunization disruption,Vaccine coverage decline,Immunization service interruption,Vaccine-preventable disease resurgence,Herd immunity gaps,Public health system resilience,Health service disruptions,Pandemic impact on immunization,Childhood vaccination delays,Missed vaccination opportunities,Health inequities in immunization,Supply chain interruptions for vaccines,Vaccine stockouts,Community-level disease outbreaks,Maternal and child health outcomes,Surveillance gaps in immunization programs,Catch-up vaccination strategies,Immunization program recovery,Morbidity and mortality from preventable diseases,Global immunization coverage trends.

1. Introduction

The COVID-19 pandemic has exposed the fragility of essential health services. Disruptions to routine immunization programs, which provide preventive vaccination against a range of infectious diseases, have been particularly concerning. Vaccines—widely considered one of the most successful interventions in public health history—not only protect vaccinated individuals but also provide herd immunity within the community, helping to safeguard vulnerable populations from outbreak risks and the consequent morbidity, mortality, and costs. Disruptions to vaccination services increase the potential for pockets of susceptibility to build within the population.

Although nearly all countries have experienced disruptions, their duration varies, as do their effects on coverage and disease epidemiology. Slumping vaccination coverage during pandemic lockdowns is a global concern, especially in countries with fragile health systems that were already facing challenges to vaccine supply chains, health service access, and community demand. Vulnerable populations are of particular concern, as they often remain inaccessible due to factors including conflict, dislocation, concern about disease exposure, and other barriers. Major delays in Covid-19 vaccine introductions are likely in the very communities

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that faced the biggest risks during the pandemic, challenging future elimination efforts. Declines in coverage increase the risk of future outbreaks and the re-emergence of diseases previously under control and place additional strain on Health Ministries and funding agencies.

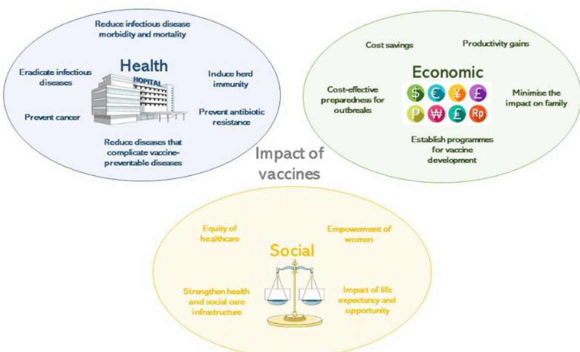

Fig 1: Impact of Vaccines; Health, Economic and Social Perspectives

1.1. Background and Significance

Routine immunization is one of the most effective public health measures for reducing childhood mortality from vaccine-preventable diseases. Global efforts to promote these services have resulted in unprecedented levels of coverage in many countries. Despite these achievements, country-specific data indicate significant inequalities and incremental declines in childhood-vaccination coverage since 2016. These are now compounded by serious disruptions to routine services caused by the COVID-19 pandemic. Such interruptions signal not only increased immediate risks of outbreaks related to individual vaccines—but also the potential resurgence of entire vaccine-preventable diseases in communities and countries that were near or had surpassed their herd-immunity thresholds.

Preventable deaths from outbreaks are already being reported in some at-risk populations, and the longer the disruptions to routine vaccination persist, the greater the risk to all vulnerable people—both those who have currently missed vaccines and generations yet to be born. Policy-makers, immunization-programme managers, and public-health officials are critically aware of this threat and are applying lessons from previous large-scale health emergencies to mitigate impacts, maintain essential services whenever possible, and enable the rapid recovery of routine vaccination coverage when catch-up campaigns become the priority. Nevertheless, there is no shortage of convergence on adaptation strategies. Furthermore, for the majority of countries, vaccination coverage data—often the most reliable information source—face their own period of disruption as an inevitable consequence of the pandemic.

Equation 1: Coverage, protection, and the "susceptible fraction"

Let:

- N = total population size
- C = vaccination **coverage** (fraction vaccinated; e.g., 0.90 = 90%)
- e = vaccine **effectiveness** against infection/transmission (0 to 1)
- I = fraction **effectively immune** due to vaccination
- S = fraction still **susceptible** (not effectively immune)

Step-by-step

1. Out of a population fraction C vaccinated, only a fraction e are effectively protected (in this simplified model).
2. Therefore, the immune fraction from vaccination is:

$$I = e\,C$$

3. The susceptible fraction is whatever remains:

$$S = 1 - I = 1 - eC$$

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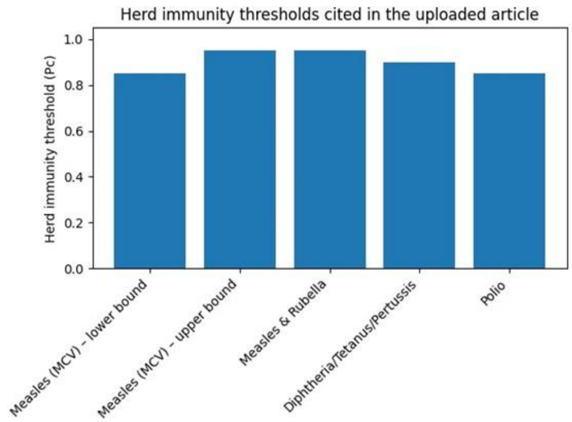
Interpretation (matches the paper's logic): when routine coverage drops, $C \downarrow \Rightarrow I \downarrow \Rightarrow S \uparrow$, creating "pockets of susceptibility."

2. Policy Implications and Stakeholder Roles

Public health policy frameworks governing routine immunization must reflect the specific risks of SAEs. Major funding institutions should factor appropriate models of risk into their investment decisions for immunization programs. Importantly, the urgency about new disease threats posed by emerging pathogens with pandemic potential must not distract from the need for nation-level efforts to sustain R.I. programs and bolster resourced strategies to reduce the public health impact of disruptions. These reactions usually occur in low- and middle-income settings but may also pertain to high-income countries where R.I. networks have been stressed by budget cuts. Sustained or enhanced support from global and regional organizations is a prerequisite to ensuring equitable access to immunization services and WHO, Gavi and the World Bank will continue working with national governments, development partners and funding agencies to provide the necessary financial resources and assistance for response and recovery activities.

Proactive engagement of other health sector actors, especially non-governmental organizations that play a fundamental role in immunization programs, helps prepare for the risk of disruptions. The operational components of routine immunization programs should be kept intact, and funding conditions should be applied to all health sector actors involved in R.I. delivery during major non-natural or disease outbreaks, whether home–or internationally driven. At the same time, responding to disease threats requires vigilance and investment, even within the health sector, as investment and operational compromise in one part of the system inevitably affect the integrity of another.

The direct and indirect effects of the pandemic on immunization services—trends clear in the limited data available—pose an alarming risk of avoidable morbidity and mortality, particularly for fully immunized children but affecting all who become susceptible to vaccine-preventable diseases. Countries report increased vaccine-preventable disease transmission, including measles, tetanus, polio, Bordetella pertussis, yellow fever, and, among adults, syphilis. Surveillance reports an upsurge in infectious keratitis and traumatic blindness in children attributable to the non-use of anti-measles and anti-rubella vaccination services. Outbreaks of diphtheria, poliomyelitis, and measles due to declined vaccination coverage levels have already occurred in some countries affected by COVID-19. Resurgence of other vaccine-preventable diseases and outbreaks attributed to interruptions in vaccinations has been predicted.



2.1. Governmental policy frameworks

Governments in many nations have established carefully considered and adaptive policies to uphold immunization services while managing the COVID-19 pandemic response. Planning and maintaining routine immunization services are, however, challenging. Priority vaccination services, such as those related to COVID-19, have led to shifts in funding, staffing, logistics, and supply chain management, demonstrated changes in patterns of access by mothers and caregivers, and diverted the operational focus of health authorities and partners. These priority adjustments are affecting uptake and quality of routine immunization and other essential child health interventions. Policymakers,

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funders, technical agencies, and operational partners must work together to respond effectively and address the different dimensions of the situation. These need to reflect the local epidemiology of vaccine-preventable diseases, address restrictions to access, resolve logistics and supply chain difficulties, and community engagement and communication concerning vaccine hesitancy.

2.2. International collaboration and funding

The public-private financing model underlying WHO's Expanded Programme on Immunization, established in 1974, still provides the foundation for the global effort to establish and sustain immunization programmes in all nations. Its modular structure enables individual modules to be funded and operated separately yet contributes to the common goal of immunizing all children against vaccine-preventable diseases. The financing is derived from many sources, including bilateral and multilateral development aid, public-facing and philanthropic foundations (e.g., the Bill & Melinda Gates Foundation) and also from a number of vaccine manufacturers that provide low-cost supplies to developing countries. Despite this international funding, the provision of immunization services is primarily the responsibility of national and local governments.

The World Bank and UNICEF provide assistance in the recovery phase by offering emergency funds on non-concessional terms to enable countries to maintain the delivery of essential health services, including immunization, during periods of acute service disruption. Furthermore, once basic services are established, the focus shifts to implementing catch-up immunization campaigns to close the vaccination gaps and restore coverage levels. Catch-up campaigns can be implemented by either national governments or international non-governmental organizations (NGOs)—for example Médecins Sans Frontières and Operation Mobilisation—all of which continue to provide, accept and act on requests for assistance in restoring vaccination coverage levels.

Equation 2: Herd immunity threshold from transmission dynamics

Step-by-step derivation

3. If only fraction S is susceptible, then transmission scales by S:

$$R_{\text{eff}} = R_0\, S$$

2. Herd immunity means transmission can't sustain itself:

$$R_{\text{eff}} < 1$$

4. Substitute $R_{\text{eff}} = R_0 S$:

$$R_0 S < 1$$

4. Divide both sides by R_0 (positive):

$$S < \frac{1}{R_0}$$

5. Since $S = 1 - I$, immunity must satisfy:

$$1 - I < \frac{1}{R_0}$$

6. Rearrange:

$$I > 1 - \frac{1}{R_0}$$

So the **critical immune fraction** is:

$$I_c = 1 - \frac{1}{R_0}$$

That is the classic herd immunity threshold *in terms of immunity*.

2.3. Partnerships with non-governmental organizations

Non-governmental organizations (NGOs) and civil society play an important role in routine immunization (RI) programs and in promoting and sustaining demand for vaccines. The interruption and modification of RI during the COVID-19 pandemic reduced the capacity and effectiveness of many such activities, decreasing confidence in vaccines and impacting demand for non-COVID-19 vaccination. As many countries plan adaptations or recovery of RI, communication with communities, parents, and caregivers is

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especially important for restoring confidence in routine vaccination.

Although essential immunization services remained predominantly accessible during the pandemic, in many areas demand for vaccines fell markedly. Supply-and-demand issues can overlap, as declines in demand can lead to fewer sessions being organized or lower attendance, even when the vaccines are available. In the context of multiservice delivery or outreach, vaccine hesitancy or reluctance associated with COVID-19 vaccination or stigma associated with use of the health system may reduce access to other routine services.

3. Drivers of Disruption

Disruptions to routine immunization activities arise from a mix of operational, supply chain, health system, and workforce factors. Operational challenges, such as travel and social distancing requirements, restricted people's movements, limiting outreach service access in remote areas. In some locations, mobile teams were consolidated or deployment changed, increasing the distance people were required to travel to receive services. These changes have disproportionally affected marginalized communities and those with emerging vaccination coverage inequalities.

Interruptions to the supply chain of cold chain, safety and medical waste management, and the distribution of vaccines, diluents, and consumables continue, resulting in localized stock-outs. Shortages of essential health commodities, including routine vaccines, pose a serious challenge to immunization services. Widespread travel bans and trade restrictions halted shipments and delayed procurement of vaccine-related supplies. Disruptions to recruitment and redeployment of staff skilled in vaccination delivery, in combination with competing demands from other health services and the social impact of COVID-19, risk leaving underlying health system weaknesses unaddressed. An over-burdened health work-force and increasing disease burden in un-immunized children who become infected with vaccine-preventable diseased greatly reduces health personnel availability.

3.1. Operational and logistical challenges

Child immunization programs are frequently disrupted by operational or logistical challenges, resulting in missed opportunities for vaccination. Such disruptions are exacerbated during health crises, including the COVID-19 pandemic. The degree to which routine immunization services must be altered or suspended for the broader health system to cope with an emergency is dictated by the vulnerability of that system, the nature of the emergency, and the resilience of the supply chains, manufacturers, and vaccine research networks. When essential services cannot be provided, vaccine-eligible children are often missed. In the absence of catch-up campaigns appropriately focused on the highest-risk cohorts and areas, there is a consequent decline in coverage.

Disruption of vaccination services and a reduction in the use of health services during public health emergencies can be expected to lower vaccination coverage. However, modelling an overall shift in routine vaccination delivery or scaling down the number of health services provided brings greater insight. Three stages of routine vaccination service provision in the event of an emergency are considered: no delivery; delivery, with a substantial reduction in vaccine-eligible cohorts; and delivery, covering all age cohorts but with an increase in missed opportunities.

Equation 3: Convert herd immunity threshold into a required coverage level

From Section 1, $I = eC$. To achieve herd immunity we need $I \geq I_c$.

Step-by-step

4. Requirement:

$$eC \geq 1 - \frac{1}{R_0}$$

3. Divide by e (assuming $e > 0$):

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$$C \geq \frac{1 - \frac{1}{R_0}}{e}$$

So the **coverage threshold** is:

$$C_c = \frac{1 - \frac{1}{R_0}}{e}$$

Key insight: if disruptions reduce C, then $C < C_c$ implies $R_{\text{eff}} > 1$ and outbreaks become likely—exactly the mechanism described in the paper.

3.2. Supply chain interruptions

Considerable interruptions persisted in the routine supply of vaccines and other immunization-related supplies during the COVID-19 pandemic. Disruption of supply chains outside of major emergencies is not common, and the consequences for countries using supplies from a single produced have been clear. An initial problem detected in COVID-19 immunization was the rapid shutdown of supply chains for non-COVID vaccines caused by the pivoting of production to COVID vaccines. Subsequently, the production of COVID vaccines resulted in increased demand on other raw materials and components that had been in long-standing, high-volume use and that had been maintained at minimum inventory levels. This combination led to shortages and interruptions in the timely delivery of non-COVID health products, ranging from antimalarial medicines to personal protective equipment.

At the same time, inequities along the supply chain were more visible than ever, and the consequences more profound: supplies delivered on time and of good quality had little or no effect in communities without the people, products, systems, and services to administer and utilize them appropriately. Within Gavi-eligible countries experiencing disruption of the COVID-19 vaccine delivery, the delay in vaccine delivery was attributed primarily to higher economic cost and a lack of strong logistical preparation and systems. The lack of continued resourcing and support for other health products, activities, systems, and partnerships was evident, and proposals to minimize the potential impact on countries in relation to oxygen supplies in particular were made.

When surveillance indicates a rising incidence or outbreak of a vaccine-preventable disease, public health authorities must respond to the situation risk-based by launching whatever intervention might maximize synergies for restoring immunity. If this can be achieved within a relatively small time window, such as weeks to a few months, public health authorities should design, reschedule, or consider interrupting routine immunization services temporarily to support targeted campaigns. If changes to routine immunization services can be synchronized with a catch-up campaign, they should be considered even if the usual trade-offs of campaign dynamics remain unfavourable. When the suspension of routine immunization services is not feasible, vaccination activity should focus on highest-risk localities indicated by surveillance data.

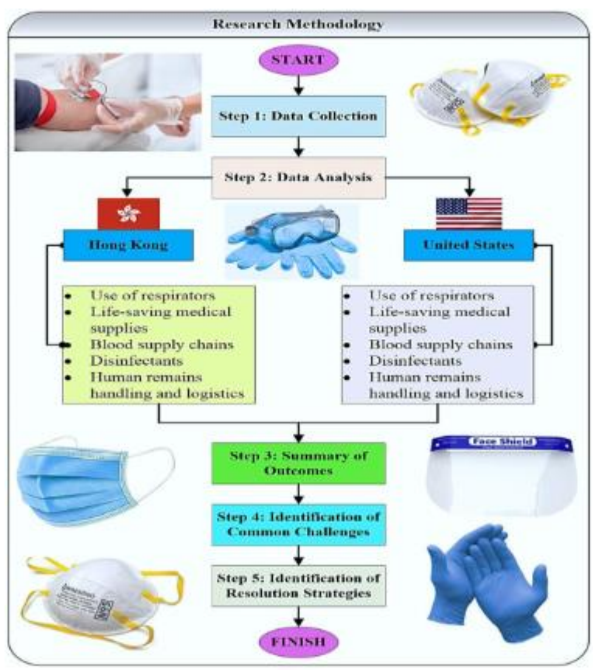

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Fig 2: Healthcare Supply Chain Management

3.3. Health system and workforce factors

The disruption of routine immunization services could be anticipated when considering health system and workforce factors. Health system weaknesses—relevant at all levels—were exacerbated during the pandemic. Health worker shortages, related to disease, burnout and restrictions on movement, created delays in the implementation of prevention campaigns and the provision of routine immunizations. Such weaknesses led to reduced or postponed vaccination services in many countries, which, when compounded by missed vaccinations, further contributed to declining vaccination coverage. Health services often lack dedicated financing for planned campaigns. In some settings, essential health services beyond COVID-19 have been deprioritized, yet these preventative activities can curtail future transmission of vaccine-preventable diseases. In the global context of a diminishing number of workers with vaccination experience, any additional interruptions represent a significant loss of capacity.

Operational limitations and modal shifts for transport and freight during the COVID-19 pandemic negatively impacted routine immunizations. Disruptions in all modes of transport—road, air, sea, and rail—overstrained already fragile supply chains for vaccines and essential supplies, at least temporarily. Utilization of alternative transport routes may have increased costs and time. National health systems became increasingly dependent on funding from external development partners, many of whom mobilized support in response to the pandemic. However, the continued lack of government funding to sustain routine immunization services remains a recurring concern.

4. Public Health Consequences

Routine immunization programs are designed to prevent the spread of vaccine-preventable diseases in populations that have sufficient levels of immunity to achieve herd immunity. When vaccination coverage, particularly the coverage of the first dose of measles-containing vaccine (MCV), declines, the risk of outbreaks of vaccine-preventable diseases resurfaces. Outbreaks of yellow fever, measles, polio, cholera, hepatitis A and B, diphtheria, and pertussis have occurred since 2019, fuelled by a combination of falling vaccination coverage due to the COVID-19 pandemic, the absence of disease-targeted preventive campaigns, and the secondary consequences of the pandemic. Interruption of vaccine supply, either through closed manufacturing plants or the repurposing of production for COVID-19-related vaccines, has posed additional risk, while war in Ukraine has complicated the provision of essential services.

The probability of a resurgence of vaccine-preventable diseases mirrors the trend in vaccination coverage. Vaccine-preventable disease outbreaks occur when vaccination coverage declines sufficiently for transmission of disease within the community to exceed the threshold for herd immunity. The MCV coverage required to limit measles outbreaks is estimated to be between 85% and 95%, with 85% necessary to prevent rapid spread in populations with high levels of vaccine-seronegativity and 95% needed for containment in low-vaccine virus-reservoir and orchestrated-transmission settings. Vaccination coverage for diphtheria-tetanus-pertussis (DTP) decline also raises concern about possible resurgence of diphtheria, and warned that re-emergence of smallpox could be catastrophic in an unvaccinated world. Canada has raised the alarm over resurgence of polio in several countries. An outbreak prediction model for polio indicated a 267% increase in the amount of expected polio outbreaks, based on rising global prevalence of vaccine-derived polio isolates.

In Israel, mumps and measles were highlighted as increased risks, and experiences from prior years indicated that mumps transmission tends to increase during periods of mass gathering among young adults. The regularity with which these diseases transmit tends to directly correlate with the measles vaccination coverage of younger cohorts. High levels of transmission in these cohorts may lead to an increased risk of measles re-introduction when these groups

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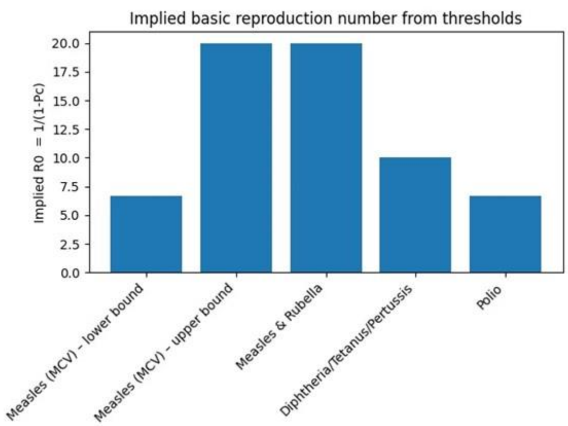
visit countries where the vaccination coverage is significantly lower.



4.1. Vaccination coverage declines

Vaccination coverage declines resulting from major disruptions in routine immunization programmed have been observed worldwide. These declines may take different forms, including a reduction in the overall number of administered vaccine doses, a decrease in the coverage of selected vaccines or vaccines given at specific ages, and a lower geographical or community-level coverage. Although short-term declines in coverage are concerning, determining their potential public health impact is more complex. Even superficial declines can create immunization gaps in a population, potentially jeopardizing herd immunity. Predicting these changes requires a detailed understanding of coverage, its disparity within regions and communities, historical epidemiology, and the biology and epidemiology of vaccine-preventable diseases. Many of these issues can be monitored using routine data sources, yet their interpretation and understanding require close collaboration between immunization and disease-control programmes. Where major extrapolations are concerned, the use of a mathematical modelling approach is useful.

Recent years have witnessed extraordinary coverage declines. The COVID-19 pandemic was exceptional in the sheer scale of its effects, the extent of the global vaccine deficit, the rapidity of the upsurge in cases and deaths that began in early 2020 and is likely to continue in its aftermath, and the still-uncertain longer-term racier. Disruptions caused by other natural disasters, armed conflicts, and political upheaval are not new; their sequelae can be seen in the past history of any nation. Yet the modern response to these extraordinary and often interlocking stresses on vaccination programmes has been distinct: the efforts to minimize morbidity and mortality attributable to a delay in the normal functioning of all essential services, including childhood vaccination. Decisions on maintaining essential services, ramping up catch-up campaigns and supporting supply-chain reliability have frequently been made with little or no use of data other than the collective experience of the global health community in dealing with such situations. Although such pragmatic responses are inevitable in emergencies, they must be complemented and informed by more detailed monitoring and research.

Equation 4: Using the article's stated thresholds to infer "implied R_0"

- Measles (MCV): **85%–95%**
- Measles & rubella: >**95%**
- Diphtheria/tetanus/pertussis: >**90%**
- Polio: >**85%**

If we assume "threshold P_c" is approximately I_c (i.e., perfect protection, $e = 1$), then:

$$P_c = 1 - \frac{1}{R_0}$$

Solve for R_0:

Step-by-step

5. Start:

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$$P_c = 1 - \frac{1}{R_0}$$

4. Subtract 1:

$$P_c - 1 = -\frac{1}{R_0}$$

5. Multiply by -1:

$$1 - P_c = \frac{1}{R_0}$$

5. Invert:

$$R_0 = \frac{1}{1 - P_c}$$

That lets you translate the paper's thresholds into an "implied transmissibility level" (illustrative—this is a simplified mapping).

4.2. Immunization gaps and herd immunity thresholds
Population immunity against vaccine-preventable diseases depends on high vaccination coverage, not only overall but also for every cohort of susceptible individuals. Outbreaks and resurgence of diseases can occur in populations with lowered herd immunity thresholds. The acquired immunity for most vaccine-preventable diseases fades within a few years and booster doses are indicated. Disrupted immunization services limit the timely and appropriate administration of both routine vaccines and vaccine boosters. Failure to meet herd immunity thresholds will result in outbreaks and resultant further morbidity and mortality in populations that have already been impacted by COVID-19.

Immunization programs must ensure that each cohort of children, adolescents and adults receives the vaccinations appropriate for their age. Severe disruptions of routine immunization activities will lead to successive cohorts of diminishing population immunity, and these gaps will have independent impacts on the risk of outbreak for different diseases. Immunization programs can minimize this risk by identifying populations at higher risk for disease and outbreak, designing and introducing targeted supplementary vaccination activities to protect these groups in a timely manner, and assessing vaccination coverage in a timely manner. Maintaining coverage levels above herd immunity thresholds for all vaccine-preventable diseases in every country of the world must remain a priority for all stakeholders.

4.3. Risk of outbreaks and resurgence of vaccine-preventable diseases According to the World Health Organization (WHO), the COVID-19 pandemic created conditions conducive to the transmission of vaccine-preventable diseases. Lower vaccination coverage increases the risk of outbreaks, particularly in countries already experiencing outbreaks of measles or polio. The U.K. Joint Committee on Vaccination and Immunization (JCVI) warned that reduced coverage for childhood vaccinations raised the risk of outbreaks of vaccine-preventable diseases such as measles, mumps, and rubella. Resurgence of poliovirus transmission and detection of vaccine-derived poliovirus also represent a major risk, particularly in countries with low vaccination coverage, insufficient routine immunization, and inadequate surveillance for acute flaccid paralysis.

Routine immunization coverage and the reporting of sentinel surveillance indicators highlighting the risk of vaccine-preventable disease outbreaks and epidemics at the country level have also been incorporated into the WHO COVID-19 strategy dashboard.

5. Monitoring, Surveillance, and Data Considerations

Administrative data on immunization coverage can provide good estimates when derived from valid, up-to-date, and consistently applied definitions. Comprehensive routine immunization coverage estimates require assessments covering all regions and populations as well as methods that allow for a breakdown of coverage by different population subgroups. Where coverage cannot be accurately assessed, additional data sources such as population registers or models can be critical. Supplementary data on the number of

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newborns and children within each target group is also necessary, as is information on the timing of scheduled contacts and a routine-data quality assessment.

During major programmatic disruptions, routine immunization coverage generally continues to decline and longer-term trends can only reflect the lack of recovery in routine services. Yet, given the historical declines observed in periods of major disruption (such as the seasonal drop during monsoon flooding in some parts of South Asia), repeated assessments of sentinel sites can indicate whether coverage is being maintained. Similarly, supplementary surveillance data can improve understanding of the risk of outbreaks and disease resurgence. The absence of outbreak data contributes to a poor understanding of the potential impact of vaccination-export bans associated with international crises, so sentinel-pattern monitoring of disease-activity indicators is warranted. With regard to data quality, heightened attention to supply of one or more vaccines suggests that similar attention should be given to the logistics of vaccine delivery within countries. In addition, exploration of how adaptations to routine immunization programs during periods of disruption alter risk for these procedures may usefully inform future programs.

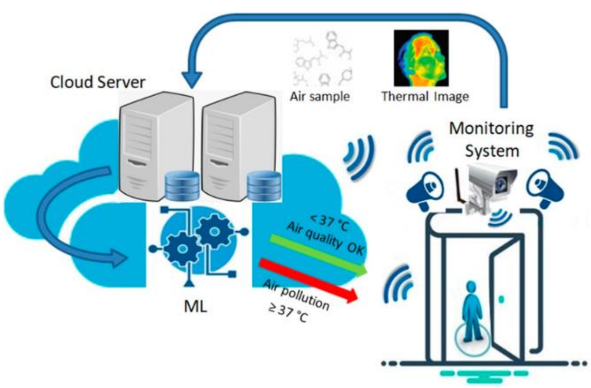

Fig 3: Secure Monitoring System for IoT Healthcare Data in the Cloud

5.1. Data quality and measurement of coverage

Population immunity, especially in lower-income countries, is at least partially reliant on accurate estimates of vaccine coverage (the proportion of the population who are fully vaccinated). Such estimates for diphtheria-pertussis-tetanus (DPT) vaccination effectively combine data from routine, campaign, and survey sources. However, the propensity for many countries to rely disproportionately on either routine reporting or survey estimates, especially when the data favour a conclusion of little or no change in coverage, can mask longer-term trends and obscure areas with urgent unmet need. Improved joint population estimates of total and under-used vaccination during the early disruption phase are thereby needed to support targeted risk assessments. Future estimates of coverage over the wider period of disruption should quantify the extent of immunity gaps and the associated risk of outbreaks.

In addition to estimating vaccination coverage, supply and distribution vulnerabilities should ideally be considered through a systems approach to any individual supply chain's overall operational readiness, addressing availability, capacity, capability, and resilience across a calibrated monitoring framework spanning the whole system. Concurrent sentinel surveillance of population immunity levels at high-risk transitions is also essential, as such immunological assessment remains the most direct means of confirming protection against disease and detecting emerging threats to the immune status of populations. The quality of these sentinel immunological data and information systems is critical for generating usable conclusions regarding population immunity against vaccine-preventable diseases, their accuracy, and interpretation.

5.2. Sentinel surveillance and outbreak detection

Systematic measurement of vaccination coverage can be supplemented by sentinel surveillance for vaccine-preventable diseases. Well-functioning sentinel surveillance monitors the epidemiology of a small number of critical conditions or diseases and provides evidence that supports public health planning and response. Data generated by such surveillance can inform decision-making by providing timely warnings of potential outbreaks and the need for

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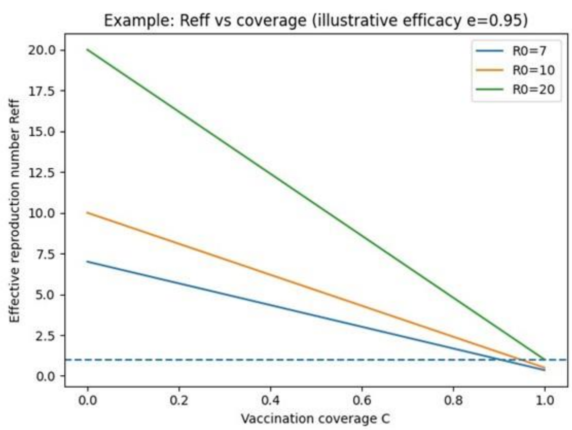
special intervention. Even when vaccination coverage levels decline, the continued operation and communication of sentinel surveillance for vaccine-preventable diseases is crucial, as the sudden rise in a vaccine-preventable disease's incidence may indicate an accelerated loss of herd immunity locally or within circulating populations. An increase in cases may also serve as an early warning to guide catch-up vaccination campaigns, particularly as the increasing risk of disease may be enhanced by the service access limitations imposed by the health emergency. Guided illustration of local-level need and demand, adoption of alternate local supply to shorten supply-lines, and encourage replenishing of local suppliers for the next HEP activity can offer communities visible indications that vaccination is caring, is responsive to local demands for need, and that Safety-Nets must be two-way.



5.3. Monitoring adaptations during disruptions

The effectiveness of routine immunization systems is compromised during periods of disruption. Thus, it is especially important to monitor coverage levels and transmission of vaccine-preventable diseases by sentinel surveillance during such times. Coverage in the first half of 2021 decreased in more than one quarter of countries with immunity monitoring in place through the WHO Regional Office for Europe. A decrease in routine immunization coverage, particularly with measles vaccines, places countries at increased risk for outbreaks, even with relatively low numbers of cases reported. Countries need to ensure that sentinel surveillance systems continue to detect re-emergence of vaccine-preventable diseases, especially in the context of reduced reporting and diagnostic capacities. Disruption responses should be designed to complement the longer-term recovery of routine immunization systems. Such responses should monitor the effectiveness of adaptations made during disruption for implication in prevention and recovery operations.

6. Mitigation and Recovery Strategies

Investments to maintain essential services during the COVID-19 pandemic mitigated some of the adverse impacts of the suspension of routine immunization on vaccination coverage. Nevertheless, in many high-burden settings, the disruptions led to additional unvaccinated cohorts and widening immunization gaps for DTP3 and measles vaccines. Where catch-up campaigns were feasible and evidence-based, they offered the possibility of preventing outbreaks and controlling resurgence of vaccine-preventable diseases. Active pediatrician involvement, whether as primary deliverers, supporting nearby ministries of health, or offering vaccination at their facilities, could offer potential solutions. Other essential primary health care functions, most especially sexual and reproductive health, also needed to be maintained.

Turnaround vaccinations for sub-optimal COVID-19 vaccines, coupled with anti-poliovirus activities holding the threat of a dump-and-burn ultimatum, emphasize the importance of preventing unlinked, Special Projects in Major Emergencies processes disturbing otherwise-smooth vaccination deliveries. Strong support for the adoption and use of formal Commercial-off-the-Shelf supply chain solution components capable of managing real-time collection and analysis of surveillance planning, demand forecasting, and supply logistics can help to pre-position stocks, stage supplies along-transit corridors, support robustness and robustness-full audits, anticipate stock-outs, and speed re-supply recoveries during an emergency.

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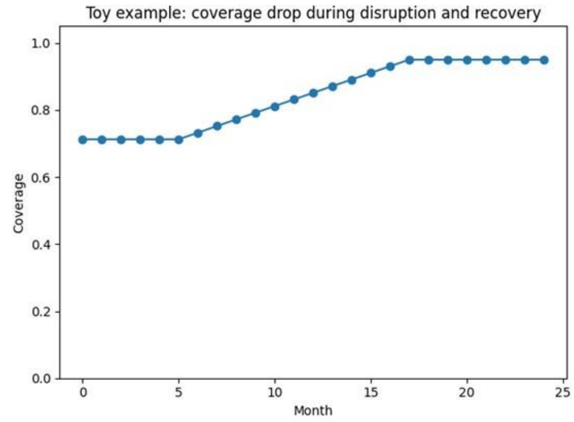
6.1. Maintained essential services and catch-up campaigns

Public health services, including routine immunization, were necessarily disrupted in many countries. Where vaccination activities were postponed, intensified catch-up campaigns for infants and children missed and overdue for routine vaccinations were implemented when conditions permitted. In many cases, these campaigns extended beyond the original target group to include older children and adolescents at increased risk of disease because of an incomplete vaccination history. Vaccination catch-up strategies also targeted other groups for whom immunization efforts may have been compromised, thereby reducing risk not only for individuals but also for community-level protection against the respective pathogens. Evidence indicated that the intensity of community transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was inversely associated with measles incidence; yet, immunization campaigns for this disease and others requiring two doses continued to be affected by disruptions in routine vaccination or coordination of campaigns.

A return to levels of population immunity capable of preventing transmission of vaccine-preventable diseases is essential. Vaccination coverage levels of over 95% are needed for both measles and rubella, levels of over 90% for diphtheria, tetanus or pertussis, and levels of over 85% for polio to reach herd immunity. Otherwise, the risk of resurgence of outbreak-prone diseases increases as cohorts of previously healthy children become susceptible. These considerations also apply for cholera, meningitis, and yellow fever vaccination, but for these diseases the necessary relative risk reductions for community protection are still not clearly defined because of uncertainties regarding habitat, effectiveness, and exposure.



6.2. Strengthening supply chains and logistics

Restoration of the vaccine supply chain was critical to resuming routine immunization and enabling catch-up campaigns in affected countries and regions. By their nature, catch-up campaigns place pressure on supply chains. This pressure is exacerbated when multiple countries or regions compete for vaccine supplies for similar campaigns. Global or regional coordination can mitigate these pressures. Where feasible, maintaining even low levels of vaccine supply during periods of reduced demand supports a more measured scaling up of catch-up activities without undue strain on supply chains.

Immunization service delivery requires efficiently functioning logistics for vaccine, diluents and consumables, refrigerators and cold-chain equipment, trained personnel and funding. While these logistics are evident, hidden challenges, such as those upstream in vaccine manufacture and supply, deserve equal attention. Manufacturers need raw materials, adjuvants and sterile vials, all of which experience increased demand when European and North American manufacturers—unaccustomed to producing substantial numbers of routine childhood vaccines—launch catch-up campaigns against diphtheria, tetanus and pertussis. Additionally, many supply-chain issues are caused not by sudden surges in demand but by endemic fragility: ‘normal business’ in many low- and middle-income countries is

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providing and assuring routine immunization vaccines and consumables, without delays or shortfalls.

6.3. Community engagement and communication

Community engagement and communication with the public are key factors influencing the success of routine immunization programs, especially during disruptions. Clarifying messages around the safety and benefits of vaccines and normalizing immunization visits can support the recovery of routine services, as evidenced by the ongoing response to COVID-19. Multiple-language messaging, community education, and outreach through trusted local figures can strengthen adherence and the prevention of disease outbreaks in communities at risk of vaccine-preventable diseases. Catch-up campaigns provide an opportunity to reach underserved communities, including those who are poorly informed, transient, or difficult to reach.

During and after disruptions, vaccinators should identify communities and subpopulations that have dropped out of the vaccination system, either temporarily or permanently. Concerns around community drop-out during the post-COVID-19 immunization catch-up remained valid, highlighting the need for intensive efforts to engage and re-activate such communities. Re-establishing a strong link with the community is critical to overcome hesitancy to immunization in communities where vaccination is either on hold, in decline, or has stopped altogether, particularly if the region has a significant population of non- or under-immunized individuals as indicated by trends in sentinel surveillance.

Equation 5: Disruption and catch-up: a simple coverage model

A simple (useful) model:

- Baseline coverage: C_0
- Relative disruption drop: d (e.g., 25% drop $\Rightarrow d = 0.25$)
- Disrupted coverage:

$$C_{\text{disrupt}} = C_0(1-d)$$

If you recover linearly back to C_0 over T months (after a disruption of D months), then for month t where $D < t \leq D + T$:

Step-by-step

6. Start point: $C(D) = C_0(1-d)$
7. End point: $C(D+T) = C_0$
8. Linear interpolation:

$$C(t) = C_0(1-d) + \frac{t-D}{T}\big(C_0 - C_0(1-d)\big)$$

6. Simplify the increment:

$$C(t) = C_0(1-d) + \frac{t-D}{T}(C_0 d)$$

This matches the paper's qualitative point: coverage "does not rebound quickly" unless catch-up is strong.

7. Conclusion

Overall, these findings imply that disruptions to routine immunization have major, persistent public health consequences. Vaccination coverage generally does not rebound quickly. By weakening herd immunity, the disturbances risk outbreaks of vaccine-preventable diseases, including measles and polio; disease resurgence can persist over many years, with susceptible cohorts becoming increasingly concentrated in high-risk areas. Therefore, it is crucial not only to protect essential health services and promote catch-up vaccination in the immediate future but also to adapt delivery strategies to the broader challenges in the health system and the socioeconomic environment.

Looking further ahead, three questions are particularly pressing. First, will the acute operational and logistical challenges of restoring routine immunization be overcome quickly enough to prevent outbreaks? Second, how are vaccination services changing to mitigate the effects of

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interruptions on herd immunity, and what extra measures are needed? Third, will national health systems and services be strengthened sufficiently to safeguard against the greater long-term risk of widespread supply chain disruptions? Ongoing, contextualized, and multilayered monitoring of routine immunization and its status will be key to answering all three.

7.1. Future Trends

Vaccination against several infectious diseases responsible for high morbidity and mortality in childhood is integrated into routine health services in many countries. Some countries have mature vaccination programs, but others are mainly dependent on external financing, technical support, and vaccine donations. Both groups have been affected. The reasons for reduced vaccination coverage during the COVID-19 pandemic are complex. Operational challenges including lockdowns and restrictions limited access to routine vaccination services, especially for communities in conflict-affected areas. Travel restrictions disrupted vaccine supply chains, and health workforce shortages due to COVID-19 illness, quarantine, or redeployment to COVID-19 services hampered routine immunization delivery.

Scarcity of financial resources is an overarching issue, even in wealthier countries. Program budgets have been severely reduced because of shifting priorities and fundraising challenges. Gavi support for vaccines against childhood infectious diseases was suspended in 2021 because of diminished demand in Gavi-eligible countries and the need to prioritize funding for COVID-19 vaccines. In 2021 and early 2022, donor countries did not mobilize funds for the COVAX Advance Market Commitment, with insufficiencies resulting in delays in deliveries of vaccines to countries eligible for support. External funding for vaccination activities and campaigns against diseases targeted by the Global Vaccine Action Plan has diminished, leading to reduced coverage levels.

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