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Emerging Viruses and Pandemics of the 21st Century: Lessons Learned and Strategies for Global Preparedness

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A B S T R A C T

The 21st century has witnessed several significant viral outbreaks, beginning with SARS in 2002, followed by H1N1 in 2009, MERS in 2012, and the transformative COVID-19 pandemic in 2019. These events have underscored the critical need for rapid global responses, resilient healthcare systems, and effective international collaboration. Other notable viruses, including Ebola, Zika, Chikungunya, and Dengue, have further highlighted the interconnected challenges of global health. This review systematically examines literature from 2003 to 2023 to explore these pandemics, their impacts, and the global responses they elicited, with a focus on strategies for future pandemic preparedness. By emphasizing lessons learned—such as the value of early detection, swift response, and coordinated international efforts—the review seeks to enhance understanding of effective management and mitigation strategies. It highlights the vital role of robust healthcare infrastructure, comprehensive public health measures, and global cooperation in protecting against emerging infectious threats and safeguarding global health.

Introduction

The 21st century has been characterized by pivotal viral outbreaks, starting with severe acute respiratory syndrome (SARS) in 2002, initiating a series of pandemics that challenged global health and emphasized the need for rapid, coordinated responses. These outbreaks reshaped public health strategies and societal norms, highlighting the importance of international collaboration in addressing emerging infectious diseases and testing the resilience of healthcare systems. [1] SARS-CoV, the causative agent behind SARS, emerged in late 2002, originating in Guangdong Province, China.

SARS-CoV swift international transmission resulted in over 8,000 cases across 26 countries.[2]

The rapid global response and containment efforts curbed the outbreak by mid-2003, demonstrating the power of coordinated action against novel viral threats.[3] Following the SARS outbreak, the world faced the influenza A H1N1 pdm 2009 virus, commonly known as swine flu, originating from a genetic combination of avian, swine, and human influenza viruses. The H1N1 pandemic, declared by the World Health Organization (WHO) in 2009, highlighted the virus's high transmissibility and prompted extensive vaccination campaigns to mitigate its impact on vulnerable populations[4,5]. Subsequently, the emergence of Middle East Respiratory Syndrome (MERS) in 2012 caused sporadic cases primarily in the Middle East.[6]

Although less widespread, MERS-CoV's high mortality rate accentuated the critical need for surveillance, swift responses, and research into potential treatments. [7,8]

However, the most profound and enduring global health crisis of the 21st century emerged with the appearance of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) [5] and the subsequent COVID-19 pandemic. [9-11] Originating in late 2019, this virus swiftly escalated into a global health emergency, overwhelming healthcare systems, triggering economic downturns, and altering everyday life on an unprecedented scale. [12-14]

Apart from these significant outbreaks, other viruses have demanded attention in the 21st century, including the Ebola virus, which reemerged in several outbreaks, notably the West Africa outbreak of 2014-2016,[15] and the Zika virus, particularly concerning its implications for pregnant women and infants due to its association with microcephaly.[16] Chikungunya and Dengue [11] outbreaks also created major global impact.[17]

The emergence and evolution of these viruses have underscored the interconnectedness of global health, the need for robust healthcare infrastructure, and the importance of proactive and coordinated responses to mitigate the impact of emerging infectious diseases. This viral outbreaks in the 21st century has reshaped our understanding of pandemics, emphasizing the necessity for preparedness, resilience, and international cooperation in safeguarding global health.[18,19] This review aimed to explore the emergence, spread and transmission, symptoms, global impact, challenges, control measures, containments, lessons learned from the emerging viruses of 21st century and preparedness measures for the mitigation of viral pandemics.

Comprehensive Review

This comprehensive review systematically examined English-language literature from 2003 to 2023, through electronic searches across prominent databases such as Scopus, PubMed, Science Direct, Up To Date, Embase, Cochrane, and Pro Quest. The search focused on significant pandemic diseases of the 21st century, including Severe Acute Respiratory Syndrome (SARS), Influenza H1N1 pdm 2009 (Swine flu), Middle East Respiratory Syndrome (MERS), COVID-19, Ebola virus, Zika virus, Chikungunya, and Dengue virus. Additionally, the search encompassed the theme of the "need for viral pandemic preparedness and mitigation." MeSH terms were applied in the PubMed database, and inclusion criteria were established for articles conducting research or presenting reviews on emerging viruses that caused pandemics in the 21st century. Articles which addressed the need for preparedness of viral pandemics and mitigations were also included, while those focusing on non-pandemic viruses or published in languages other than English were excluded. A total of 130 paper abstracts underwent initial evaluation, and 57 articles identified in the full text form. In cases where full texts were unavailable, efforts were made to contact authors for the missing content. The selected articles underwent thorough evaluation by a research team, with discrepancies resolved by a third evaluator. The final set of 57 papers provided a rich of information on emerging viruses, pandemics, and the imperative for preparedness and mitigation, with the collected material organized and categorized based on scientific content within their respective thematic areas.

Overview of emerging viruses and great pandemics of the 21st century

The first emerging virus and pandemic of the 21st century: severe acute respiratory syndrome (SARS)

Severe Acute Respiratory Syndrome (SARS), the inaugural significant pandemic of the 21st century, emerged in late 2002 and persisted into 2003. Originating in Guangdong Province, China, cases were initially reported in November 2002, presenting as atypical pneumonia. By early 2003, the outbreak had spread within China and internationally through infected travellers. A novel coronavirus, SARS-CoV, was identified as the causative agent in March 2003, believed

to have originated in bats and transmitted to humans, potentially via intermediary animals like civet cats. SARS-CoV primarily spread through respiratory droplets, with potential transmission through direct contact or contaminated surfaces. Symptoms included flu-like manifestations progressing to severe respiratory distress and pneumonia. The outbreak affected over 8,000 people across 26 countries, prompting the World Health Organization (WHO) to declare it a global health threat.[10,20,21]

Challenges included difficulties in identifying cases, rapid international spread, and shortcomings in infection control. Control measures involved quarantine, isolation, travel restrictions, and healthcare infection control. Swift global cooperation and coordinated efforts led to containment, with surveillance, case isolation, and infection control contributing to the decline. The SARS outbreak underscored the significance of global cooperation, early detection, rapid response, and transparency in managing emerging infectious diseases. It prompted research and preparedness efforts for future pandemics, emphasizing the importance of enhanced surveillance, prompt case identification, and stringent infection control measures. The experience with SARS provided valuable lessons, shaping strategies for addressing and mitigating the impact of subsequent emerging infectious threats.[10,20,21]

The second emerging virus and pandemic of the 21st century: Influenza H1N1 pdm 2009

Influenza A H1N1 pdm 2009, or swine flu, triggered a global pandemic in 2009-2010, originating from a unique combination of genetic material from pigs, humans, and birds. Initially identified in April 2009, it was labelled "swine flu" due to genetic similarities to pig viruses but was a novel strain in humans. The virus primarily spread through respiratory droplets, proving highly contagious and rapidly disseminating worldwide. Symptoms resembled seasonal flu, encompassing fever, cough, sore throat, body aches, fatigue, headache, and, in some cases, diarrhoea and vomiting. Severity varied, with high-risk groups including pregnant women, children, the elderly, those with underlying health conditions, and individuals with weakened immune systems.

The World Health Organization declared it a pandemic in June 2009, prompting global efforts to control transmission. Response measures included hygiene campaigns, mask-wearing, social distancing, school closures, travel restrictions, and vaccination campaigns. Specific vaccines were developed and prioritized for high-risk groups, gradually becoming more widely available. As immunity increased through exposure and vaccination, the virus transitioned into a seasonal influenza strain, causing milder illness. The pandemic's impact underscored the importance of swift global response, public health measures, and vaccine development in managing emerging infectious threats. The experience with H1N1 pdm 2009 influenced future pandemic preparedness and emphasized the role of vaccination campaigns in mitigating the impact of novel influenza strains. [22-25]

The third emerging virus and pandemic of the 21st century: Middle east respiratory syndrome (MERS)

Middle East Respiratory Syndrome (MERS), caused by the Middle East Respiratory Syndrome Coronavirus (MERS-CoV), emerged in Saudi Arabia in 2012, primarily affecting the Middle East with sporadic cases through travel-associated spread. Believed to originate from dromedary camels, MERS-CoV transmitted among humans, particularly in healthcare settings. Symptoms included fever, cough, shortness of breath, and pneumonia, with severe respiratory illness and a high mortality rate of around 35%, especially among those with underlying health conditions. Although the outbreak remained sporadic, the severity of the disease underscored its impact.

Control measures focused on surveillance, contact tracing, isolation of suspected cases, and infection control in healthcare settings. Travel advisories were issued for affected areas, emphasizing precautions for travellers. The MERS outbreak prompted extensive research into the virus, its transmission dynamics, and potential treatments and vaccines. The relatively lower number of reported cases compared to other respiratory infections highlighted the importance of understanding the virus's severity and implementing targeted control measures.

The experience with MERS emphasized global cooperation in addressing emerging infectious diseases, contributing to advancements in research, preparedness, and control strategies. Despite the lower global impact in

terms of cases, the high mortality rate underscored the critical need for continued vigilance and collaborative efforts to mitigate the impact of novel coronaviruses and other emerging pathogens.[25-28]

The fourth pandemic of the 21st century -SARS CoV-2 (COVID -19)

The fourth pandemic of the 21st century is attributed to the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), causing the COVID-19 disease. Part of the coronavirus family, which includes SARS and MERS, the virus likely originated from bats and possibly transmitted to humans through an intermediate animal host.

First identified in Wuhan, China, in December 2019, SARS-CoV-2 swiftly evolved into a global crisis. Its high transmissibility and asymptomatic spread led to a pandemic declaration by the World Health Organization in March 2020. The virus primarily spreads through respiratory droplets and can also spread through contact with contaminated surfaces. A challenge is its ability to spread from asymptomatic or pre-symptomatic individuals.

Symptoms of COVID-19 vary and can range from mild to severe, including fever, cough, shortness of breath, fatigue, loss of taste or smell, and gastrointestinal symptoms. Severe cases may lead to pneumonia, acute respiratory distress syndrome (ARDS), organ failure, and death. Older adults and those with underlying health conditions face a higher risk of severe illness. The global impact of the pandemic has been profound, affecting public health, economies, social interactions, and healthcare systems. Governments implemented measures like lockdowns, travel restrictions, mask mandates, and testing to control the virus spread.

Efforts worldwide led to the rapid development and authorization of multiple COVID-19 vaccines, aiming to provide immunity and reduce transmission. Treatments, including antiviral medications and monoclonal antibodies, were employed to manage symptoms. SARS-CoV-2 continually evolves, giving rise to different variants with varying characteristics, impacting vaccine effectiveness and necessitating ongoing monitoring.

The long-term consequences of the pandemic extend to global health, economies, education, mental health, and societal structures. Weaknesses in healthcare systems were exposed, socio-economic disparities widened, and daily life underwent significant changes with the widespread adoption of remote work and virtual communication. The COVID-19 pandemic stands as a multifaceted challenge, prompting unprecedented global collaboration in research, vaccine development, and public health strategies. The ongoing evolution of the virus and its enduring societal impacts underscore the need for continued vigilance and adaptive responses to emerging infectious threats.[29 – 34]

Over-view of viruses and pandemic of the 21st century

Ebola Virus

The Ebola virus, identified in 1976, causes severe illness and death in humans and primates. Originating in the Democratic Republic of Congo, outbreaks occurred in Sudan and Congo simultaneously during the first recognized instances. The West Africa 2014-2016 outbreak, starting in Guinea and spreading to Liberia and Sierra Leone, was one of history's largest and most devastating, with over 28,000 cases and 11,000 deaths, causing significant social and economic disruption. The 2018 outbreak in North Kivu, declared over in June 2020, faced similar challenges. In February 2021, a new outbreak emerged in North Kivu Province, while the country dealt with another in Equateur Province. Challenges included ongoing conflicts and instability. The Ebola virus has five species, with Zaire, Sudan, Bundibugyo, and Tai Forest causing human illness. Believed to originate from bats, transmission to humans occurs through handling or consuming infected animals, and human-to-human transmission through bodily fluids.

Symptoms, appearing 2-21 days post-exposure, include fever, weakness, muscle pain, headache, vomiting, diarrhoea, rash, impaired organ function, and in severe cases, bleeding. Ebola progresses rapidly, with fatality rates ranging from 25% to 90%, varying by outbreak and virus strain. Outbreaks historically occurred in Central and West Africa, where limited healthcare infrastructure exacerbated the impact. Public health measures for prevention include isolating infected individuals, contact tracing, infection control, safe burials, and public awareness campaigns. Efforts to develop Ebola vaccines and treatments have shown promise in clinical trials. Supportive care, maintaining hydration, managing

symptoms, and appropriate medical care aim to improve patient survival. The global impact of Ebola outbreaks underscores the importance of ongoing research, preparedness, and international collaboration in addressing emerging infectious diseases.[35-38]

Zika virus

The Zika virus, belonging to the Flaviviridae family, is primarily transmitted by Aedes mosquitoes, gaining global attention in a significant 21st -century outbreak. First identified in Uganda's Zika Forest in 1947, sporadic human cases occurred in Africa and Asia.

The major outbreak began in Brazil in 2015, rapidly spreading across South and Central America, the Caribbean, and parts of North America. Transmission occurs primarily through mosquito bites, particularly Aedes aegypti and Aedes albopictus, but can also happen through sexual contact, mother-to-child transmission, and in rare cases, through blood transfusions or organ transplantation. Notable concerns arose due to the Zika virus's association with congenital abnormalities, particularly microcephaly in newborns, prompting travel warnings and precautions for pregnant women. The virus has also been linked to Guillain-Barré syndrome, a rare neurological disorder.

Preventing mosquito bites is crucial for reducing Zika transmission, involving the use of insect repellents, wearing protective clothing, using mosquito nets, and eliminating breeding sites. Pregnant women are advised to avoid travel to affected regions.

Diagnosis involves specific laboratory tests detecting the virus's genetic material. There is no specific antiviral treatment, and supportive care, such as rest and hydration, is recommended for symptomatic individuals. Research efforts post-2015 have focused on understanding the virus, its transmission dynamics, and its impact on human health, particularly during pregnancy.

Public health responses involve mosquito control measures, surveillance, and public awareness campaigns to prevent transmission. The Zika outbreak underscores the importance of global vigilance, research collaboration, and public health strategies in addressing emerging infectious diseases with potential severe consequences, particularly for vulnerable populations like pregnant women and their newborns. [39-42]

Chikungunya virus

Chikungunya virus, identified in Tanzania in 1952, gained 21st -century attention due to significant outbreaks beyond its traditional range. The 2005 Indian Ocean islands outbreak, starting in La Réunion, spread to India and neighbouring areas, affecting hundreds of thousands. Subsequent expansions reached Asia, including India, Thailand, and the Philippines, and the Americas, causing outbreaks in the Caribbean, Central, and South America. Transmitted by Aedes mosquitoes active during the day, the virus causes an abrupt onset of symptoms, including fever, severe joint pain, muscle pain, headache, nausea, fatigue, and rash. Joint pain can persist for weeks to months, leading to inflammation and stiffness. While rarely fatal,

Chikungunya symptoms can be severe and disabling, impacting daily activities. Long-term complications may include chronic arthritis persisting for months or years.

Diagnosis involves detecting the virus in blood, and there is no specific antiviral treatment. Medical care focuses on managing symptoms with rest, hydration, pain relievers, and anti-inflammatory medications. Prevention includes reducing mosquito exposure through repellents, long-sleeved clothing, mosquito nets, and eliminating breeding sites. Chikungunya outbreaks pose a global health concern due to rapid spread potential, impact on individuals' quality of life, and potential strain on healthcare systems, especially in non-endemic regions. The virus's expansion highlights the need for public health measures, research, and global cooperation to mitigate its impact and prevent further geographical spread.[43 – 46]

Dengue virus

Dengue fever, a longstanding public health concern, has experienced notable emergence and resurgence in the 21st century, marked by increased global incidence and geographic spread. Around half of the world's population is now at risk, with millions of reported cases annually, affecting regions like Southeast Asia, the Americas, Africa, and the Western Pacific.

The expansion of dengue's geographic range is linked to urbanization, heightened travel, population growth, inadequate sanitation, and the adaptability of Aedes aegypti and Aedes albopictus mosquitoes, the primary vectors. These mosquitoes thrive in urban environments,

breeding in stagnant water found in various artificial containers, contributing to increased transmission risk in urban areas. Dengue poses a substantial burden on public health systems, causing significant morbidity and mortality. Severe cases can lead to life-threatening conditions such as dengue haemorrhagic fever or dengue shock syndrome. The economic impact, attributed to healthcare costs and lost productivity, is a growing concern.

Climate change, characterized by increased temperatures and rainfall, is associated with the spread of dengue, creating favourable conditions for mosquito breeding and extending the disease's geographic range. Prevention and control efforts involve mosquito control measures, including eliminating breeding sites and using insecticides. Ongoing research efforts have led to the development and approval of dengue vaccines in certain countries. The emergence of dengue in the 21st century underscores the importance of sustained surveillance, prevention, and control measures to mitigate its impact and reduce global transmission. [47-51]

Ensuring resilience: reasons for and measures in viral pandemic preparedness

Being prepared for pandemic viruses is imperative for safeguarding public health, minimizing social and economic impact, and fostering global stability. A proactive approach to preparedness entails collaborative efforts among governments, healthcare organizations, research institutions, and communities. This readiness is driven by several key reasons. Firstly, it protects public health by implementing measures such as early detection, case isolation, contact tracing, and preventive actions, thereby reducing the spread of infectious diseases. Swift preparedness and response efforts are essential for minimizing the severity and duration of pandemics, leading to a reduction in illness, hospitalizations, and fatalities. Ensuring the resilience of healthcare systems is another crucial aspect, involving the provision of adequate medical supplies, hospital beds, ventilators, and trained professionals to handle increased demand.

Moreover, preparedness measures contribute to economic stability by mitigating disruptions to businesses, trade, and employment. Global health security is enhanced through collaborative efforts between nations, sharing information, resources, and expertise to effectively combat the cross-border spread of viruses. Social disruption caused by pandemics, such as school closures and travel restrictions, can be minimized through clear communication, robust public health strategies, and targeted interventions.

Investment in research and development for vaccines, antiviral medications, and treatments is integral to preparedness, enabling rapid deployment of effective interventions when novel viruses emerge. Empowering individuals and communities with knowledge, resources, and tools through education and communication campaigns is a cornerstone of preparedness, fostering community resilience. Additionally, preparedness involves an adaptive response to emerging variants, with ongoing monitoring, research, and the development of variant-specific countermeasures. Ethical considerations, such as ensuring equitable access to healthcare resources, protecting vulnerable populations, and upholding human rights, are emphasized throughout preparedness efforts, ensuring a comprehensive and ethically guided approach to addressing the challenges posed by pandemic viruses.[52-57]

Strategic actions: preparedness measures for mitigating viral pandemics

Being prepared for viral pandemics necessitates a comprehensive approach involving individuals, communities, and governments. On an individual level, staying informed through reliable sources, practicing good hygiene, maintaining social distancing, and having a personal emergency kit are crucial measures. Adhering to health guidelines, including wearing masks and getting vaccinated when available, further enhances individual preparedness.

At the community level, public awareness campaigns, development of emergency plans, readiness of healthcare systems, and collaboration among stakeholders are vital components. Supporting vulnerable populations and ensuring equitable access to resources are emphasized community strategies. Governmental preparedness involves establishing early detection and surveillance systems, developing and updating comprehensive response plans, maintaining strategic stockpiles, strengthening supply chains, and fostering global collaboration. Investment in research and development for diagnostics, treatments, and vaccines, along with a transparent communication strategy, forms a key part of government-led preparedness. The multi-faceted approach recognizes the interconnectedness of individual

actions, community resilience, and government leadership in effectively responding to viral pandemics. Flexibility and adaptability are deemed essential, with regular drills and simulations serving as tools to test the efficacy of preparedness plans in an evolving situation. Ultimately, a coordinated effort across these three pillars—individual, community, and governmental—is imperative for enhancing global readiness and response to viral pandemics. [52-58]

In conclusion, the 21st century has borne witness to a series of profound viral outbreaks that have reshaped our understanding of global health, compelling societies and healthcare systems worldwide to adapt rapidly to new challenges.

From the emergence of Severe Acute Respiratory Syndrome (SARS) in 2002 to the relentless impact of the COVID-19 pandemic, each outbreak has underscored the critical importance of preparedness, global collaboration, and proactive responses to emerging infectious diseases.

These viral outbreaks have not only tested the resilience of healthcare infrastructure but also laid bare the interconnectedness of our world.

They emphasized the necessity of robust surveillance systems, swift response mechanisms, and equitable access to healthcare resources.

Lessons learned from SARS, H1N1, MERS, Ebola, Zika, Chikungunya, and Dengue outbreaks have ignited advancements in vaccine development, therapeutic interventions, and public health strategies.

The emergence and evolution of these viruses have necessitated continuous adaptation, urging societies to embrace innovative solutions, harness scientific advancements, and foster international solidarity. As we navigate the aftermath of these pandemics, the 21st century's lessons reaffirm the imperative of unified global efforts, resilient health systems, and unwavering commitment to safeguarding human health and well-being against the unpredictable nature of emerging infectious diseases.

Author Contributions

Shyamala Ravikoti: Investigation, formal analysis, writing—original draft. S. K. Mohanasundari: Validation, methodology, writing—reviewing. Mamta Choudhary:—Formal analysis, writing—review and editing. Annamreddi Leelavathi: Investigation, writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Consent to Participate Not applicable.

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