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Ebola Vaccination: From Outbreak Control to Global Preparedness

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Abstract

Ebola virus disease (EVD) is one of the most dreadful and lethal viral infections, continuously generating threatening impacts on the health of the global population, especially in low-resource environments. This review provides an overview of Ebola vaccines, focusing on virology, vaccine development, clinical trials, regulatory approval, deployment plans, and ethical issues. Recombinant viral vector platforms have seen the development of successful vaccines, with the most prominent example being rVSV-ZEBOV, which has proven highly effective in outbreak situations. Both the safety and real-world effectiveness of these vaccines during Ebola outbreaks have been proven through clinical trials, such as the innovative ring vaccination studies, which have revolutionized the process of controlling Ebola epidemics. Vaccination as part of global preparedness systems, aided by stockpiling, emergency use authorizations, and augmented cold-chain logistics, has shifted responses toward preventive actions rather than merely reactive containment. Despite these successes, challenges remain associated with vaccine equity, access, duration of immunity, and community acceptance. Innovation in next-generation and multivalent vaccines, as well as approaches to deploying them ethically and equitably, is necessary to enhance outbreak preparedness. Overall, Ebola vaccines have transformed epidemic management and will serve as a valuable tool for handling future emerging infectious diseases.

Keywords: Ebola virus disease, Ebola vaccines, rVSV-ZEBOV, ring vaccination, outbreak preparedness, vaccine equity, global health security

INTRODUCTION

Ebola virus disease (EVD) is a dangerous and commonly deadly zoonotic disease caused by viruses of the genus Orthoebolavirus* of the Filoviridae* family. It manifests itself by acute fever, severe weakness, headache, muscle pain, and gastrointestinal symptoms (vomiting and diarrhea) and, in some cases, leads to hemorrhagic manifestations and multiorgan failure. The infection is transmitted during direct contact with the blood or other bodily fluids of infected persons, infectious materials, or animals, especially in healthcare or caregiving facilities where safety precautions are not adequate [1].

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Ebola has been an epidemic threat to the population since its initial outbreaks in Central Africa in 1976 and has mostly hit sub-Saharan African countries since. Early Ebola outbreaks were generally limited in scale and confined to remote geographic areas; however, the 2014–2016 West African epidemic marked a critical turning point, revealing the virus's capacity for widespread transmission, urban spread, and devastating impact on already fragile healthcare systems. This outbreak revealed significant gaps in surveillance,

rapid diagnostics, community interaction, and global preparedness, leading to significant changes in outbreak response plans [2]. These lessons have been used to benefit subsequent outbreaks with reduced death tolls and coordinated international response efforts, resulting in faster containment and better clinical care.

Despite such improvements, Ebola remains a major threat because of frequent spillover incidences, population dynamics, and health system weaknesses in endemic areas. Vaccination against Ebola in this context has become a very important preventive measure. Individual protection, especially for healthcare workers and those in frontline response, is provided by vaccines and is strategic to interfere with transmission via targeted methods like ring vaccination [3].

The presence of efficient vaccines has revolutionized the control of outbreaks by alleviating the number of persons at risk, conserving healthcare resources, and supplementing other elements of public health such as surveillance, isolation, and therapeutic interventions. In addition, vaccination activities enhance the trust and involvement of communities when combined with culturally sensitive response measures. Even though effective vaccines exist against some species of the Ebola virus, continued research is necessary to develop extensive protection against all clinically relevant strains [4]. In general, the introduction of vaccination into the system of Ebola preparedness and response is an essential step toward the minimization of morbidity, deaths, and the overall effect of further outbreaks on the world [3].

EBOLA VIRUS: STRUCTURE AND PATHOGENESIS

The Ebola virus is an enveloped and filamentous RNA virus that falls under the family Filoviridae and is characterized by distinct morphology and high pathogenicity. The genome of the virus is non-segmented and negative-sense, single-stranded RNA approximately 19 kb long and encodes seven indispensable proteins containing nucleoprotein (NP), viral proteins VP35, VP40, VP30, VP24, the surface glycoprotein (GP), and the RNA-dependent RNA polymerase (L), which are located in a helical nucleocapsid and laid within a host-derived lipid envelope (Figure 1) [5].

Viral glycoprotein GP creates spikes on the surface that facilitate host cell binding and cell entry; VP40 is a central figure in virion assembly and budding that connects viral structure to infectivity and spread. Ebola virus infection is achieved by direct contact with the blood or body fluids of an infected person, infectious material, or infected animals (such as nonhuman primates and fruit bats) after entering through mucosal surfaces or broken skin. After 2–21 days, the disease progression commences with nonspecific signs of fever, malaise, headache, and myalgia, and moves to severe involvement of the gastrointestinal tract, dehydration, and metabolic imbalance as viral replication increases (Figure 1) [6].

The Ebola virus infects endothelial cells and hepatocytes as the infection spreads systematically, causing hemorrhagic manifestations, shock, and multiorgan dysfunction in severe manifestations. The host immune response is significantly disoriented, whereby the viral proteins VP35 and VP24 prevent the production and signal transduction of interferon, which allows viral replication to occur and viral proliferation to take place extensively (Figure 1).

The excessive release of pro-inflammatory cytokines and chemokines by infected immune cells results in a cytokine storm that causes vascular leakage, tissue damage, and hemodynamic instability, and the extensive apoptosis of lymphocytes causes immunosuppression and impaired adaptive immune responses [7]. The combination of interconnected mechanisms of viral structure, transmission, disease progression, and dysregulation of the host immune system justifies the serious clinical course and high mortality of Ebola virus disease and emphasizes the importance of integrated curative and preventive approaches in single and multiple phases of infection, as illustrated in the integrative scheme (Figure 1) [8].

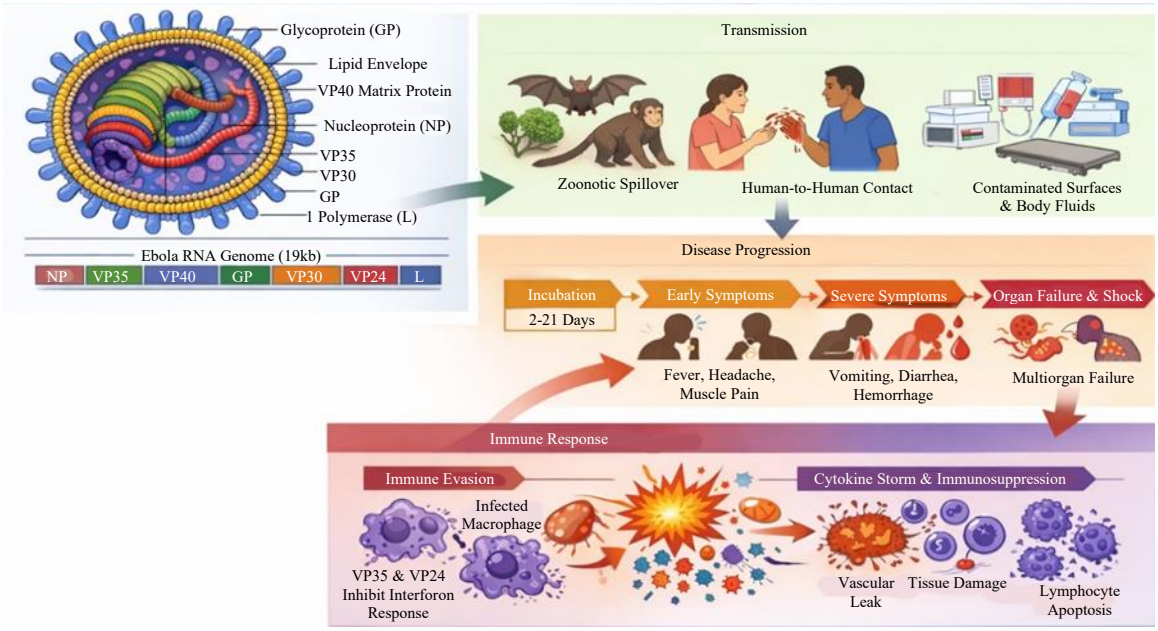

Figure 1. Ebola virus structure, transmission, and pathogenesis.

DEVELOPMENT OF EBOLA VACCINES

The history of developing Ebola vaccines spans decades and has been influenced by major biological, technical, and logistical factors. Initial research on Ebola vaccines began shortly after the virus was first discovered in 1976 and was mainly centered around the comprehension of viral structure, pathogenesis, and immune correlates of protection in animal models, especially nonhuman primates. Development was slow because of unpredictable and intermittent outbreaks, inadequate funding, ethical limitations to human experiments, and the need for high-containment biosafety facilities [9]. Early vaccine strategies, such as attenuated whole-virus vaccines and subunit vaccines, showed poor immunogenicity or safety concerns, and it became clear that more effective and scalable platforms were required. Progress in molecular biology resulted in the creation of recombinant viral vector platforms, which was an important advance in Ebola vaccinology. These systems use genetically engineered viruses, including adenoviruses, modified vaccinia Ankara, and vesicular stomatitis virus, to transfer the Ebola virus glycoprotein gene into host cells, which results in robust humoral and cellular immune responses without pathogenic exposure to the Ebola virus [10]. Viral vector vaccines offered various benefits, such as rapid induction of immunity, robust T-cell immunity, and flexibility, to various Ebola virus strains, rendering them especially effective in an outbreak environment. One of these, the recombinant vesicular stomatitis virus-based vaccine rVSV-ZEBOV, commercialized as Ervebo, was a breakthrough in the prevention of Ebola. This live attenuated vaccine incorporates the glycoprotein of Zaire ebolavirus instead of the native VSV glycoprotein such that the vaccine virus can express Ebola GP with controlled replication in the host. After vaccination, there is a strong activation of innate immunity and the quick production of GP-specific neutralizing antibodies and T-cell responses, which offers fast and effective protection [11]. The single-dose protection of the vaccine and its suitability in ring vaccination plans during outbreaks made it ideal, and its proven efficacy and safe tolerability resulted in regulatory approval. Overall, the transition from early experimental strategies to sophisticated recombinant vector vaccines represents significant scientific innovation and has revolutionized global preparedness and response to Ebola outbreaks [12].

CLINICAL TRIALS OF EBOLA VACCINES

The development of clinical trials on Ebola vaccines followed a systematic process that involved preclinical trials, phase-based human trials, and novel outbreak-based study designs, which eventually offered strong evidence of vaccination safety and effectiveness. Preclinical testing was fundamental in developing proof of concept and safety before human testing, where candidate vaccines were first

studied for immunogenicity and dose optimization in small animal models, typically mice and guinea pigs [13]. Nevertheless, nonhuman primates were the ultimate preclinical model since they are an excellent replica of human Ebola virus disease in viral kinetics, immune responses, and clinical severity. Such studies continually showed that vaccines that caused high Ebola glycoprotein-specific antibody and T-cell responses could control lethal viral challenges and thus proceed to human trials, as summarized in Table 1. The initial assessment of Ebola vaccines in humans occurred in phase I clinical trials and involved mainly safety and immunogenicity in small groups of healthy adult volunteers [14]. These trials revealed that most of the vaccine candidates were well tolerated, and adverse events were mostly limited to mild or moderate, self-limiting symptoms of fever, injection-site responses, and fatigue. Notably, phase I trials demonstrated the stimulation of humoral and cellular immunity, which confirmed the preclinical observations and provided the basis for dosing decisions and immunization regimens used in further trials (Table 1). Phase II and phase III clinical trials expanded the assessment to larger and more heterogeneous groups, including those who live in or near Ebola-affected zones [15]. The goals of these trials were to determine vaccine efficacy while continuing to monitor safety and immune durability. Traditional designs of randomized controlled trials were modified to cover ethical issues during high-mortality outbreak conditions, and the findings showed high protection against Ebola virus disease in people who were vaccinated, which justified regulatory approval and emergency use as indicated in Table 1. Another breakthrough in efficacy testing was a pilot ring vaccination trial in ongoing Ebola epidemics [10]. This strategy entailed the vaccination of contacts and contacts-of-contacts of confirmed cases, which in effect formed a protective barrier to interrupt transmission. Ring vaccination trials presented strong real-world data of fast and high coverage, despite requiring only a single dose, and showed both individual and communal advantages *(*Table 1). These phases of clinical trials altogether enabled Ebola vaccines to rise out of experimentation and become tested and validated health tools, reshaping approaches to outbreak control and prevention [16].

Table 1. Summary of major preclinical and clinical trials of Ebola virus vaccines.

Vaccine candidate	Vaccine platform	Preclinical model	Clinical trial phase	Study location	Study population	Key outcomes
rVSV-ZEBOV (Ervebo)	Recombinant vesicular stomatitis virus (live-attenuated viral vector)	Nonhuman primates (rhesus and cynomolgus macaques)	Phase I, II, III	USA, Europe, Guinea, DRC	Healthy adults, outbreak contacts	Demonstrated strong immunogenicity, rapid onset of protection, high vaccine efficacy, acceptable safety profile.
ChAd3-EBO-Z	Chimpanzee adenovirus vector	Nonhuman primates	Phase I, II	USA, UK, Africa	Healthy volunteers	Induced robust antibody and T-cell responses; required booster for sustained immunity.
Ad26-ZEBOV / MVA-BN-Filo	Heterologous prime-boost viral vector (adenovirus + MVA)	Nonhuman primates	Phase I, II, III	Africa, Europe	Adults in endemic regions	Strong and durable immune responses; good safety profile.
rVSV-ZEBOV Ring Vaccination Trial	Recombinant viral vector	Nonhuman primates (supporting data)	Phase III (ring vaccination design)	Guinea	Contacts and contacts-of-contacts	Near-complete protection in immediate vaccination group; validated ring vaccination strategy.
DNA-based Ebola Vaccine	Plasmid DNA vaccine	Mice, guinea pigs	Phase I	USA	Healthy adults	Safe but limited immunogenicity compared to viral vectors.
Inactivated Ebola Virus Vaccine	Inactivated whole virus	Small animal models	Preclinical only	Laboratory-based	Not applicable	Safety concerns and limited efficacy prevented clinical advancement.

REGULATORY APPROVAL AND DEPLOYMENT

The approval and introduction of Ebola vaccines to the market have been based on expedited but sound models that aim to reconcile the demands of immediate health concerns with strict safety and efficacy standards. The World Health Organization has been the leading coordinating entity at the global level by initiating mechanisms like Emergency Use Listing, prequalification, and recommendations by advisory expert groups, which allow swift evaluation of vaccine quality, safety, and programmatic suitability for use in areas at risk of outbreaks [17]. Meanwhile, regulatory authorities of most countries, especially the US Food and Drug Administration, approved Ebola vaccines under expedited drug development pathways such as Fast Track designation, Priority Review, and the use of animal efficacy data together with human immunogenicity and safety results. These adaptive regulatory methods were necessary since standard large-scale efficacy trials are difficult to conduct for sporadic diseases with high fatality rates such as Ebola [18]. In active outbreaks, emergency use authorizations, conducted to allow investigational or conditionally approved vaccines to be rolled out within a short period, were helpful to protect frontline healthcare workers and to enable ring vaccination measures in contacts and contacts-of-contacts of confirmed cases. This kind of emergency use was coupled with increased safety surveillance, aggressive pharmacovigilance, ethical supervision, and informed consent measures that ensured that practical data gathered during deployment could contribute to the ultimate benefit-risk profile as well as aid eventual complete licensure [19]. Beyond regulatory decisions, distribution capacity and cold-chain management have played a key role in the successful implementation of the Ebola vaccine. Most Ebola vaccines, in particular the live recombinant viral-based vaccines, are highly sensitive to temperatures (to the extent that they need extremely low temperatures, typically − 60°C to −80°C), which poses significant logistical challenges in remote and resource-deprived locations where Ebola outbreaks are frequent. To cope with these issues, international logistics, such as special freezers, temperature-controlled transportation systems, temperature monitoring of the product, and power outage and transportation contingency plans, have been mandatory [20]. Educating health personnel on the effective storage, handling, and administration of vaccines has also been important in avoiding wastage and ensuring effective usage. Hastened regulatory approval systems, emergency use authorizations, and strong distribution and cold-chain solutions have collectively facilitated the prompt and efficient delivery of Ebola vaccinations. Not only have these experiences transformed the response to Ebola outbreaks, but they have also offered a framework for regulatory preparedness and vaccine deployment plans to respond to future emerging infectious disease threats [21].

EBOLA VACCINATION STRATEGIES

Ebola vaccination strategies have evolved to balance rapid outbreak containment with long-term preparedness, with ring vaccination, preventive immunization of high-risk groups, and integration into broader immunization frameworks forming complementary approaches. The ring vaccination strategy has proven particularly effective during active outbreaks, as it focuses on vaccinating confirmed case contacts and contacts-of-contacts to create a protective buffer that interrupts transmission chains. This targeted approach allows limited vaccine supplies to be used efficiently while providing both direct and indirect protection to communities [22]. Successful ring vaccination relies on rapid case detection, comprehensive contact tracing, risk assessment, timely vaccination, and continuous follow-up of vaccinated individuals, all of which function as an integrated sequence of actions as depicted in Figure 2. Community engagement and trust are essential for identifying contacts and ensuring vaccine acceptance, as delays or refusals can weaken the protective ring and allow further spread. Complementing this reactive strategy, preventive vaccination of high-risk populations offers a proactive layer of protection [2]. Healthcare workers, laboratory staff, burial teams, and outbreak responders are consistently exposed to the Ebola virus during both outbreak and inter-epidemic periods and, therefore, benefit from preemptive immunization. Preventive vaccination reduces healthcare-associated transmission, preserves workforce capacity, and strengthens early outbreak response, effectively reinforcing the containment steps illustrated in Figure 2 by reducing the number of susceptible individuals at the frontline. Beyond targeted approaches, integrating Ebola vaccines into national and global immunization and preparedness programs is critical for sustainability and rapid deployment [23].

Such integration involves maintaining vaccine stockpiles, training healthcare workers, strengthening regulatory and logistical systems, and aligning Ebola vaccination with surveillance and emergency response infrastructures. At the global level, coordinated mechanisms ensure equitable access, timely distribution, and standardized guidance across countries at risk. The operational logic of these integrated systems mirrors the structured pathway shown in Figure 2, where surveillance, vaccination, and monitoring operate as interconnected components rather than isolated interventions [17]. Together, these strategies demonstrate that effective Ebola control depends on a layered vaccination approach that combines reactive ring vaccination, proactive protection of high-risk groups, and systematic integration into immunization and preparedness frameworks, thereby enhancing outbreak control, resilience, and long-term public health security [24].

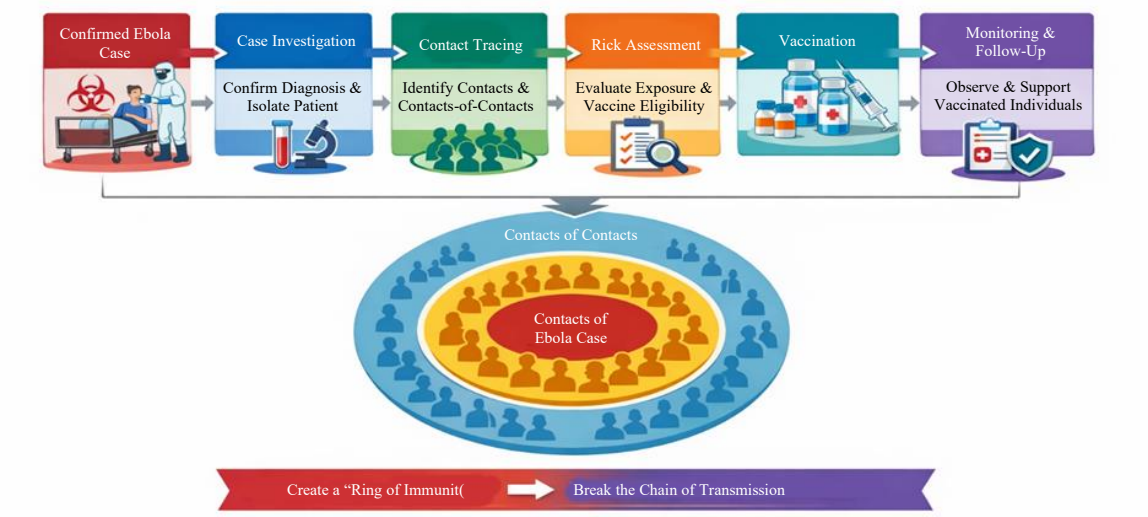

Figure 2. Ring vaccination strategy for Ebola outbreak control.

SAFETY, EFFECTIVENESS, AND LIMITATIONS

The safety, efficacy, and limitations of Ebola vaccines are critical factors in the formation of vaccination policies and emergency response plans. Large-scale trials and practical use have demonstrated that Ebola vaccines have a good safety profile, with most of side effects being mild to moderate and short-lived. Local reactions, such as pain, redness, and swelling at the injection site, are common, as are systemic reactions, e.g., fever, fatigue, headache, myalgia, and arthralgia), which may follow shortly after vaccination and resolve independently [25]. There are few cases of serious adverse events, and no major long-term safety concerns have been noted; however, continuous pharmacovigilance is vital in vulnerable populations. Ebola vaccines elicit rapid and high-intensity immune responses, especially glycoprotein-specific neutralizing antibodies and cellular immunity, which are strongly correlated with disease protection. The antibody response may last several years, although its intensity decreases over time, and the duration of protection may not be consistent across vaccine platforms or between immunocompetent individuals and those with immunological disorders [26]. T-cell memory is thought to contribute to prolonged immunity, despite a decline in antibody concentrations. In some vaccines, particularly heterologous prime-boost vaccines, booster shots increase the intensity and sustainability of immune defense, which is especially significant for healthcare personnel and other high-risk groups because of continued exposure. Although these benefits exist, there are still issues of vaccine acceptance and accessibility [27]. Misinformation, fear, cultural beliefs, and mistrust of health authorities have contributed to vaccine hesitancy, hindering acceptance in some outbreak-affected communities. Logistical access is also limited by hindrances such as poor healthcare facilities, rough topography, warfare, and strict cold-chain requirements [28]. Global inequalities in vaccine distribution and access can delay delivery to vulnerable areas. To overcome these shortcomings, there must be sustained work in communities, open communication, strong health

systems, and international coordination to guarantee that Ebola vaccines realize their full potential in preventing the disease and mitigating the impact of outbreaks [29].

GLOBAL PREPAREDNESS AND FUTURE DIRECTIONS

Global preparedness for Ebola outbreaks increasingly emphasizes coordinated planning, technological innovation, and forward-looking vaccine development to ensure a rapid and effective response. Central to this approach are international stockpiling and rapid response frameworks that enable immediate access to Ebola vaccines when outbreaks are detected. Strategically maintained vaccine stockpiles, supported by advance procurement agreements and regulatory readiness, allow rapid deployment to affected regions and are closely linked with surveillance and emergency response systems [30]. The operational sequence – from early detection and stockpile activation to targeted vaccination and monitoring – is illustrated in Figure 3, demonstrating how vaccination is integrated into broader outbreak preparedness mechanisms. Decisions regarding stockpile composition and deployment priorities are informed by comparative data on licensed and investigational vaccines, including their efficacy, dosing schedules, and target virus species, as summarized in Table 2. Alongside stockpiling, advances in vaccine storage and cost reduction have significantly improved the feasibility of large-scale preparedness efforts [31].

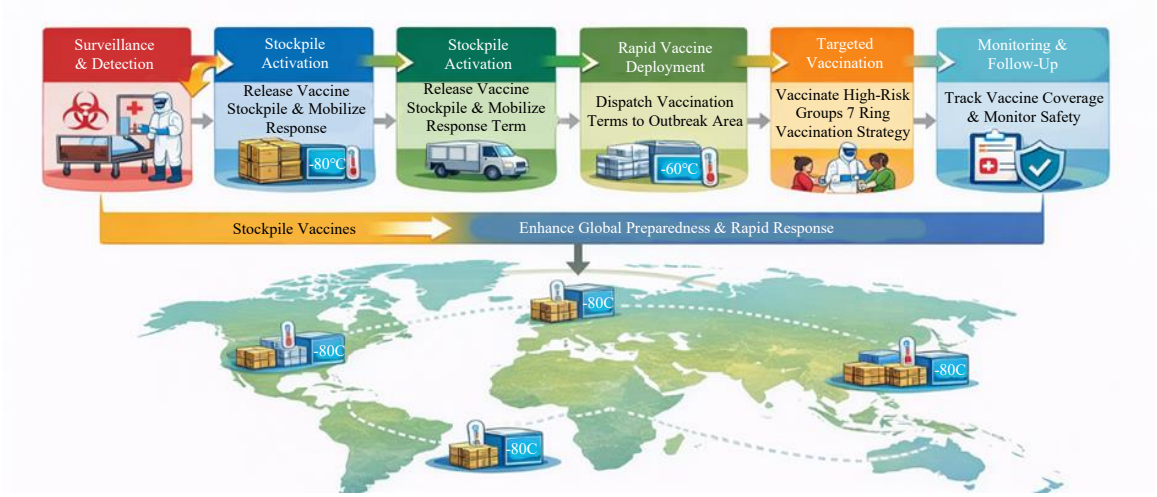

Figure 3. Role of Ebola vaccination in global outbreak preparedness.

Innovations aimed at enhancing vaccine thermostability and enabling controlled temperature chain use have reduced reliance on ultra-cold storage, lowering logistical barriers and minimizing wastage during emergency deployment. Improvements in manufacturing efficiency, economies of scale, and long-term funding commitments have further contributed to reduced per-dose costs, supporting sustainable stockpiling and preventive vaccination strategies. Variations in storage requirements, costs, and programmatic suitability among existing and emerging Ebola vaccines are highlighted in Table 2, guiding policymakers in selecting vaccines that balance effectiveness with operational practicality [32]. Looking ahead, next-generation Ebola vaccines and combination vaccines represent a critical component of future preparedness. Research efforts are focused on developing multivalent or pan-Ebola vaccines capable of protecting against multiple Ebola virus species, as well as combination vaccines that could simplify immunization strategies for high-risk populations. Novel platforms, including improved viral vectors, protein subunits, and mRNA-based technologies, offer the potential for broader protection, longer-lasting immunity, and easier deployment [33]. The envisioned role of these next-generation vaccines within preparedness and response systems is reflected in Figure 3, where vaccination functions as both a preventive and reactive tool. Collectively, strengthened stockpiling frameworks, advances in storage and cost efficiency, and continued innovation in vaccine design form the foundation of global Ebola preparedness and future outbreak resilience [34].

Table 2. Comparison of available and emerging Ebola vaccines.

Vaccine name	Vaccine platform	Target Ebola virus species	Dose regimen	Storage requirement	Clinical status	Key advantages	Limitations
rVSV-ZEBOV (Ervebo)	Recombinant vesicular stomatitis virus (live vector)	Zaire ebolavirus	Single dose	Ultra-cold (–60°C to –80°C)	Licensed	Rapid protection, high efficacy, suitable for ring vaccination	Cold-chain complexity, limited species coverage.
Ad26-ZEBOV / MVA-BN-Filo	Heterologous prime-boost viral vector	Zaire ebolavirus	Two doses (prime-boost)	2–8°C	Phase III	Durable immunity, easier storage	Slower onset of protection.
ChAd3-EBO-Z	Chimpanzee adenovirus vector	Zaire ebolavirus	Single dose ± booster	2–8°C	Phase II	Strong cellular immunity	Pre-existing vector immunity, booster needed.
Multivalent Ebola Vaccine (in development)	Recombinant viral vector / subunit	Multiple Ebola virus species	Single or multiple doses	2–8°C (target)	Preclinical / Early clinical	Broad species protection	Not yet clinically validated.
mRNA-based Ebola Vaccine (emerging)	mRNA platform	Multiple Ebola virus species	Two doses	Frozen (–20°C to –70°C)	Preclinical	Rapid design, scalable manufacturing	Stability and cost challenges.

ETHICAL AND PUBLIC HEALTH CONSIDERATIONS

The proper application of Ebola vaccines is grounded in ethical and public health considerations, especially since epidemics most commonly occur in low-resource countries with weak health systems. Vaccine access and equity remain significant ethical issues; the groups most vulnerable to Ebola tend to be affected by slow vaccine rollout, primarily due to insufficient production, high prices, and reliance on international supply chains. The principles of justice and fairness require Ebola vaccines to be distributed based on population health needs rather than economic or geopolitical influence [35]. Nonetheless, the unequal distribution of cold-chain systems, a lack of qualified medical personnel, inadequate transport infrastructure, and security conditions in conflict zones continue to hinder access. Mistrust of external health interventions, stemming from past experiences of exploitation and marginalization, is another historical factor influencing ethical vaccine deployment; thus, community engagement and culturally sensitive communication are crucial. Strengthening local health systems, facilitating regional vaccine manufacturing, and engaging community leaders in planning and delivery are essential measures for enhancing equity and acceptance [36]. Simultaneously, ethical concerns arise regarding emergency clinical trials during Ebola outbreaks, where the urgent need to find effective interventions must be balanced against individual rights. Traditional randomized controlled trial methods may be difficult to justify for a high-mortality disease, especially when there are initial signs of benefit. Challenges include obtaining informed consent under fear-inducing conditions and social disruption, avoiding the exploitation of vulnerable groups, and determining the proper use of placebo or delayed-intervention controls [37]. Innovative trial designs, such as adaptive protocols and ring vaccination trials, have been developed to overcome these issues by maximizing access to potentially useful vaccines while still yielding scientifically valid information. To uphold the principles of respect, beneficence, and justice, strong ethical oversight, transparency, and post-trial access to successful interventions must be ensured. Together, vaccine equity and ethical research are essential for building trust, ensuring equitable access, and optimizing the public health impact of Ebola vaccination programs [38].

CONCLUSION

The creation and introduction of Ebola vaccines represent a revolutionary step in managing Ebola virus disease, fundamentally changing outbreak response and global health preparedness. Historically, outbreak control depended primarily on reactive interventions (isolation, contact tracing, and safe burials) by local health authorities, which, despite being necessary, were often inadequate for rapidly interrupting transmission. The development of effective Ebola vaccines has greatly improved outbreak management by offering direct protection to at-risk individuals and enabling targeted measures like ring vaccination, which has proven highly effective in interrupting transmission chains. Vaccinating frontline responders and medical personnel has also minimized healthcare-associated transmission and conserved essential response capacity. Beyond containing active outbreaks, the availability of Ebola vaccines has enabled a transition from crisis-driven responses to proactive global preparedness. The creation of vaccine stockpiles, formalized regulatory processes, and preestablished deployment structures now enable mobilization at the first signs of an outbreak. Reactive vaccination of at-risk populations and the incorporation of vaccination into preparedness planning have increased health system resilience and minimized the broader social and economic consequences of outbreaks. Ultimately, Ebola vaccines have not only saved lives and shortened the duration of outbreaks but have also transformed global epidemic preparedness, providing a model that can be applied to other emerging infectious disease threats in the future.

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