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Cholera in Haiti

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ABSTRACT

The cholera epidemic that hit Haiti from October 2010 to February 2019 was the world's deadliest of the last 25 years. Officially, the successive waves caused 9789 deaths, although numerous additional casualties could not be recorded. The origin of this epidemic has been the subject of a controversy involving two opposing theories. The first hypothesis, put forward by renowned American academics, was that the cholera epidemic originated from the environment, due to the proliferation and transmission of aquatic *Vibrio cholerae* bacteria driven by a confluence of circumstances, i.e., the earthquake followed by a hot summer and, ultimately, heavy rainfall and flooding. The alternative hypothesis, which was subsequently confirmed by epidemiological and genomic studies, attributed the epidemic to the recent importation of cholera by UN peacekeepers recently arrived from Nepal, and to a river polluted with sewage. In late 2016, the Secretary General of the United Nations finally begged the Haitian people for forgiveness. This implicit recognition of the role of the UN in the cholera epidemic helped to fund the ongoing fight against it. Case-area targeted interventions aimed at interrupting cholera transmission were reinforced, which resulted in the extinction of the epidemic within two years. In the meantime, several phylogenetic studies on *Vibrio cholerae* during the seventh cholera pandemic demonstrated that local environmental and global epidemic *Vibrio* populations were distinct. These studies also showed that epidemics arose when the bacterium had diversified and that it had spread during transmission events associated with human travel.

1. Introduction

Cholera is a diarrheal disease caused by toxigenic strains of *Vibrio cholerae*. The bacterium is transmitted by ingesting contaminated water or food or more rarely via direct contact with an infected person [1]. Clinically, the disease is characterized by often profuse watery diarrhea and vomiting that can lead to severe dehydration and death if not immediately treated. However, many cases are asymptomatic or present only minor clinical signs, such as banal diarrhea. Cholera epidemics particularly afflict the world's poorest countries, which are characterized by limited healthcare and poor access to safe drinking water, sanitation and hygiene [WASH) facilities. That is why, when the Pan American Health Organization (PAHO, the American branch of the World Health Asscociation [WHO]) reported the emergence of cholera in Haiti on October 22, 2010 [2], the outbreak was considered by many as an almost inevitable event following the disasters that had befallen the country. More precisely, the Caribbean nation had been devastated just nine months earlier by a deadly earthquake [3]. Notwithstanding an exceptional international response, Haiti had struggled to recover. The country's capital, Port-au-Prince, was still cluttered with rubble and more than a million earthquake survivors were living in tented camps when the cholera outbreak occurred.

In point of fact, epidemics have rarely occurred in the immediate aftermath of geophysical disasters such as earthquakes, volcanic eruptions and tsunamis. In a study covering a 20-year period (1985-2005), only three moderate epidemic episodes were identified subsequent to more than 600 geophysical disasters (i.e., measles, fungal infections and malaria) [4]. Even when a disaster of this nature occurred in an area where cholera was prevalent, outbreaks did not occur, as observed in Goma, Democratic Republic of Congo, following the Nyiragongo Volcano eruptions in 2002 and 2021. Generally, the assistance provided to the affected populations during such disasters (e.g., provision of drinking water) is sufficient to prevent cholera outbreaks.

However, with more than 820,000 cases and nearly 10,000 deaths officially reported between 2010 and 2019, the cholera epidemic in Haiti was the worst in the last 25 years in terms of mortality and the second largest (after the Yemen epidemic) in terms of morbidity [5,6] (Fig. 1). In reality, study of this epidemic goes far beyond the framework of public health. The investigation of its origin, which was ultimately associated with the arrival of a contingent of peacekeepers from a country plagued by cholera, generated a scientific, political

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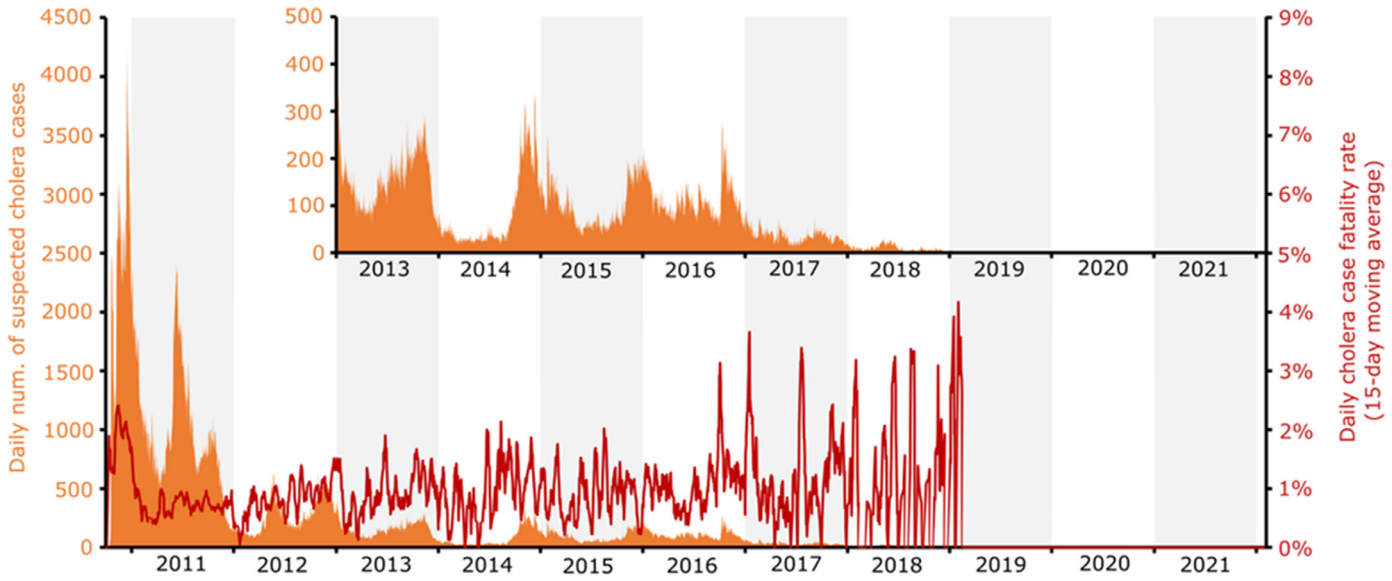

Fig. 1. Daily number of suspected cholera cases and case fatality rate in Haiti between October 2010 and February 2022. (Data source: Haitian Ministry of Public Health and Population).

and legal controversy that culminated only in December 2016 when Ban Ki-moon, the former UN Secretary General, addressed the Haitian people to ask for their forgiveness [7]. From an epistemological point of view, the epidemic sparked questions regarding the long-standing theory of cholera emergence, which postulated that cholera outbreaks arise from environmental strains of *Vibrio cholerae* that proliferate following climatic anomalies. Moreover, three years after the last case, the fact that the WHO has yet to deliver an official certification of cholera elimination in Haiti shows how difficult it is to re-examine a theory once it is considered a paradigm.

2. The onset of the epidemic

The Republic of Haiti occupies the western third of the island of Hispaniola, where the nation shares a border of more than 370 kilometers with Dominican Republic (Fig. 2). Haiti, which in 2010 had a population approximating 10 million, has been politically and economically unstable for decades. With 70% of the population living below the poverty line and record unemployment rates (50% to 70%), Haiti is a very poor country, with the lowest gross domestic product in the Americas and deep-seated inequalities [8].

On January 12, 2010, a magnitude-7 earthquake in Haiti caused a humanitarian disaster of exceptional proportions [3]. According to estimates, the earthquake killed 100,000 to 300,000 people. The epicenter was located approximately 20 kilometers west of Port-au-Prince, and many neighborhoods in the capital and the surrounding areas were destroyed. As a result, more than a million survivors were forced to settle in tented camps set up in the undeveloped areas of the city. Due to the particularly precarious situation in Port-au-Prince and the surrounding areas, the media immediately warned that an epidemic might ensue. However, as time elapsed without any major infectious events, the threat of an epidemic appeared to recede. It was only after people had lowered their guard that a cholera outbreak finally occurred, in October 2010.

However, the outbreak did not begin in the area affected by the earthquake, where the camps for displaced persons were located, but rather 100 kilometers further north, near the town of Saint Marc in the Artibonite Department [9] (Fig. 2). When the epidemic was confirmed on October 22, 2010, PAHO reported a staggering 1526 suspected cases and 138 deaths [10,11]. The following day, a thousand new cases were reported and the number of deaths totaled 194 [12]. The influx of new cases continued over the next few days, albeit less violently, reaching a total of 4714 cases and 330 deaths on October 29 [13]. During this initial phase of the epidemic, the vast majority of patients came from villages along the lower Artibonite River, especially the rice paddies in the delta (Fig. 2). Other suspected cases were reported a few dozen kilometers further upstream, near the town of Mirebalais in the Centre Department. New cases quickly appeared in neighboring departments, both to the north along the Atlantic coast and to the south in the Port-au-Prince area [9]. On November 4, Hurricane Tomas further aggravated the catastrophic situation, as flooding contaminated unprotected sources of drinking water, thereby reigniting the epidemic, particularly in Port-au-Prince and the coastal cities of northern Haiti [9] by the end of November, the outbreak had spread throughout the country, peaking at over 4000 daily cases by mid-December 2010 [14]. The presidential and legislative elections on November 27 occasioned a series of demonstrations and street blockades that further complicated the response efforts, hindering assistance for hospitals that were already completely overwhelmed with cholera cases. This first wave of the epidemic did not subside until early 2011, during the dry season between December and April. The rainy season in April 2011 triggered another sharp increase, and this trend of fluctuating epidemic waves, in parallel with the seasons and rainfall, continued for several years.

Of all the epidemic waves of cholera in Haiti, the one between late 2010 and early 2011 was by far the deadliest. Although the official death toll after six months was 4470, investigations in various urban and rural areas showed that cholera was responsible for the death of approximately 1 out of 100 inhabitants, while in some rural territories without healthcare facilities the disease killed 1 out of 20 inhabitants (5%) [15,16]. Although the northern half of the country, where these studies were conducted, was more severely affected than the Port-au-Prince area and the south of Haiti, it was estimated that during this first wave, tens of thousands of people died of cholera. Many of these deaths escaped surveillance because they perished at home or on the way to a health center. Contrary to popular belief, the Dominican Republic was not spared. During the peak of the epidemic in that touristic country in 2011, 20,851 cases and 336 deaths were reported [6]. However, compared to the 340,311 cases and 2869 deaths recorded in Haiti during the same year (in addition to the 179,379 cases and 3,990 deaths at the end of 2010), the epidemic in Dominican Republic went almost unnoticed.

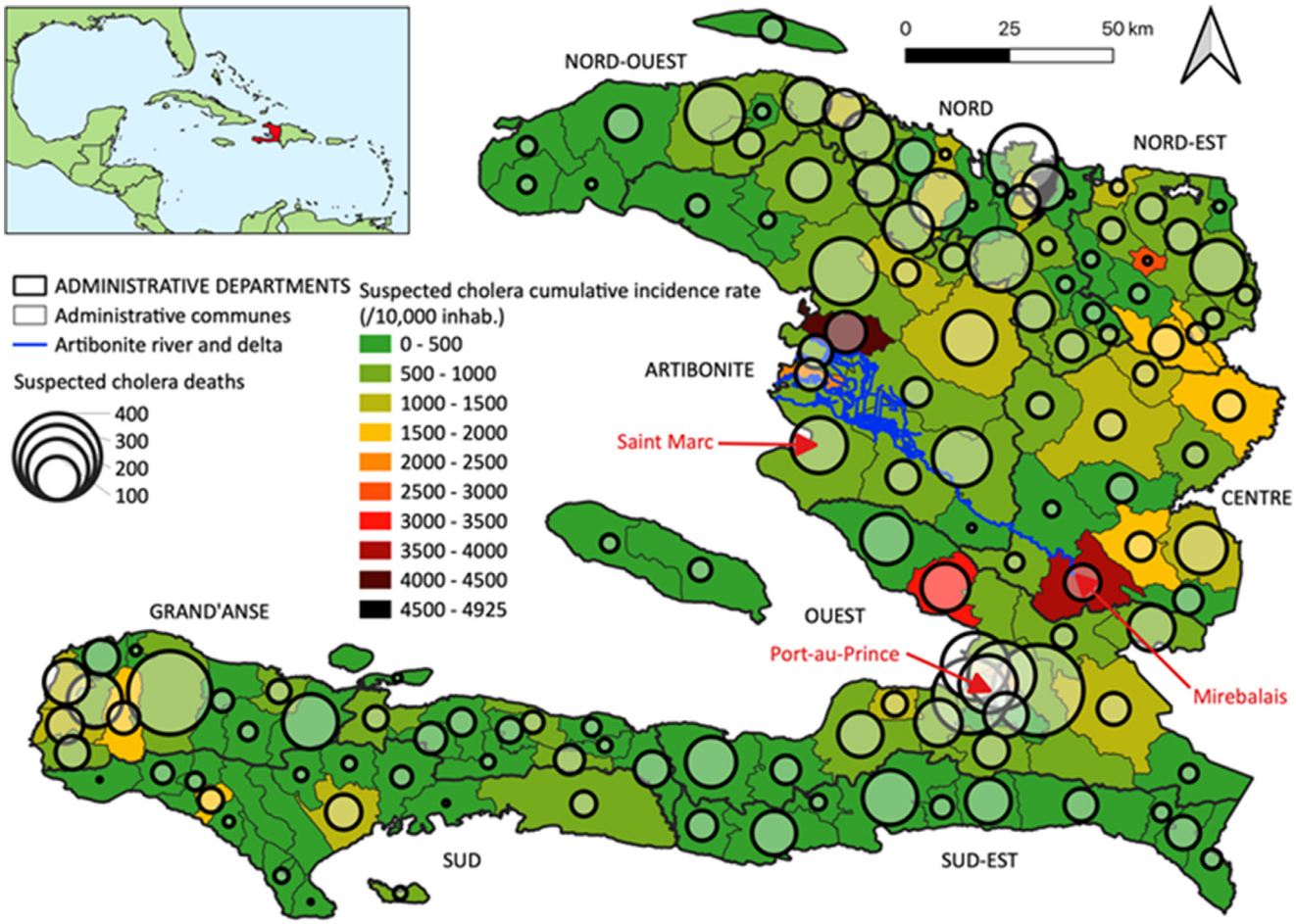

Fig. 2. Suspected cholera cumulative incidence rate and cumulative deaths in Haiti from October 2010 to February 2022 at the commune scale. Key locations cited in the text are indicated (Data source: Haitian Ministry of Public Health and Population).

3. Controversy over the origin of the epidemic

The emergence of cholera in Haiti im-mediately raised questions regarding the origin of the outbreak. At the time, Haiti was not considered a cholera endemic country, and studies showed that the 2010 epidemic was unprecedented [17]. As it occurred only nine months after the January 12, 2010 earthquake, a link was immediately postulated between the two events. However, given the distance between the Port-au-Prince metropolitan area and the Artibonite Valley, an area unaffected by the earthquake, and the time elapsed between the two events, a direct link seemed unlikely.

At the onset of the epidemic, cases were reported throughout much of the Artibonite River valley, from Mirebalais to the delta. However, the situation reports published by WHO and OCHA (United Nations Office for the Coordination of Humanitarian Affairs) quickly shifted the focus to the outbreaks in the delta and away from those around Mirebalais [18]. The maps and images depicting the evolution of the epidemic soon presented the coastal regions of Artibonite Department as the first-affected areas, from which the disease then spread through the rest of the country, including the Centre Department [18]. A group of scientists seized this opportunity to defend the hypothesis that linked cholera to climate and the aquatic environment, which had been advocated since the 1980s by Professor Rita Colwell, a specialist in the microbiology of aquatic environments [19]. Professor Colwell considers *Vibrio cholerae* first and foremost an environmental bacterium. Noting that cholera epidemics often occur in coastal regions, she postulates that in humans, the first cases were linked to the consumption of seafood contaminated with *Vibrio cholerae* following the proliferation of the bacterium in the environment due to fluctuations in plankton. Around the Bay of Bengal in South Asia, the warm and rainy monsoon periods are accompanied by an increase in water temperature, an increase in plankton concentrations and a proliferation of *Vibrio cholerae*, which grow on the plankton, and occasion an increased numbers of cholera cases Colwell insists that climatic factors (increased water temperature) favor plankton proliferation and consequently *Vibrio cholerae* proliferation.

The renowned scientist had previously distinguished herself by analyzing the determinants of the cholera wave that struck Latin America from Chile to Mexico during the 1990s. She had hypothesized that the cholera outbreak in Peru and subsequent spread of the disease through Latin America was due to the El Niño phenomenon and the coincidingly warmer coastal waters [19]. El Niño results in a reversal of the marine current that runs along the coast of South America, usually flowing from south to north, in the direction opposite to El Niño events. According to Colwell, inversion of the maritime current and the subsequent increase in water temperatures favored the proliferation of plankton and *Vibrio cholerae*, thereby triggering the first cases of cholera in humans along the Peruvian coast. This theory was initially presented at a conference and described in an article entitled "Global Climate and Infectious Disease: The Cholera Paradigm", published in *Science* and cited more than 1600 times in the biomedical literature [19]. However, certain fundamental claims presented in this article have been refuted: NASA data indicate that the El Niño phenomenon had not yet begun in January 1991, when the cholera epidemic broke out in Peru [7]. El Niño actually started several months later (in September 1991) and was of only moderate

intensity. By that time, Peru had already experienced a major cholera outbreak and the disease had spread to other South American countries. Some authors questioned the putative link between El Niño and the onset of cholera in Peru, but their publication did not have the same success as Colwell's [20]. As a result, her narrative and her environmental and climatic paradigm of cholera prevailed when the cholera epidemic struck Haiti, in 2010.

In November 2010, when scientists were questioned about the cause of the cholera epidemic in Haiti, some postulated that the bacteria were already present in the environment, specifically in the brackish waters of the Artibonite Delta [21]. They explained that the bacterium had most likely proliferated in the local aquatic environment during a particularly hot summer before the epidemic exploded. Rita Colwell described the scenario of the earthquake in January and subsequent landslides that may have modified the pH of the Artibonite waters as the "perfect storm" that triggered the subsequent cholera outbreak. Although this was only a hypothesis with no confirmatory data, Professor Colwell's word was (and still is) very much respected, and many followed her lead, explaining to the press that cholera in Haiti was just one of the many unfortunate consequences of global warming. During a visit to Haiti in August, Asfar Ali, an associate professor of environmental and global health at the University of Florida, went so far as to say that he had observed earthquake refugees using the river and ocean water directly [22]. However, no camps had been set up for people displaced by the earthquake near the Artibonite River.

In contrast to the theory that the cholera outbreak originated from ocean-dwelling bacteria, an alternative hypothesis suggested that the cholera outbreak was linked with the arrival of a contingent of Nepalese soldiers coming to relieve a garrison located a few kilometers south of the town of Mirebalais in the Centre Department, on October 8, 2010 (figure2). A few journalists had obtained confirmation of this troop movement, and upon visiting the site, they noted that wastewater from the military camp was being discharged into the environment. They also confirmed that suspected cases of cholera had visited the hospital in Mirebalais, with an influx of patients occurring before the first cases were reported in the Artibonite Delta [18]. However, these reports did not constitute an epidemiological investigation, and the testimony of the mayor of Mirebalais that cholera had begun in a village a few kilometers away, at the site of the military camp, did not carry nearly as much weight as that of experienced scientists who had been studying cholera for decades.

In October 2010, many international epidemiologists were in Haiti, working for either the PAHO/WHO or the US Centers for Disease Control and Prevention (CDC). Curiously, these experts did not seem interested in investigating the origin of the epidemic. Jordan Tappero, who was leading the CDC team in Haiti at the time, told the press that it was better to focus primarily on case management. "To really try to identify who was the individual that first suffered cholera or where that location was is nearly an impossible task, given the magnitude of the outbreak and the need for focusing energies to train healthcare providers to take care of cholera patients" [23]. This point of view was incongruent with the mission of the CDC, which was established in part to understand the mechanisms of communicable diseases through epidemiological investigations, to guide control efforts, and to help prevent similar events in the future. Nevertheless, the Haitian government did wish to understand the origin of the epidemic disaster and wound up contacting the French embassy to request technical support. Building upon the initial investigation conducted by Haitian epidemiologists, a Franco-Haitian team, led by an author of the current article (RP), conducted a detailed epidemiological study that was published in May 2011 in *Emerging Infectious Diseases*, the journal of the US CDC. Assessing the origin of the epidemic in a paper entitled "Understanding the cholera epidemic, Haiti", the researchers found that the outbreak was linked to septic tanks in a UN military camp located near the town of Mirebalais, which had contaminated a tributary of the Artibonite River [9]. According to their findings, the river water had been contaminated by a significant amount of fecal matter harboring *Vibrio cholerae*, thereby triggering outbreaks in the village of Meye (just opposite the military camp) and in the town of Mirebalais, a few kilometers downstream. The epidemic exploded a few days later in the Artibonite Delta, and cholera spread throughout Haiti in the following weeks. In the meantime, the UN Secretary General learned of these investigations and due to pressure from the media, mandated the WHO to conduct its own investigation [24]. The ensuing report, written by a panel of four scientists specialized in cholera and sanitation, confirmed the starting point of the epidemic stating that "The evidence does not support the hypotheses suggesting that the current outbreak is of a natural environmental source. In particular, the outbreak is not due to the Gulf of Mexico strain of *Vibrio cholerae*, nor is it due to a pathogenic mutation of a strain indigenously originating from the Haitian environment. Instead, the evidence overwhelmingly supports the conclusion that the source of the Haiti cholera outbreak was due to contamination of the Meye Tributary of the Artibonite River with a pathogenic strain of current South Asian type *Vibrio cholerae* as a result of human activity."

However, the WHO investigators also indicated that they believed that many factors had contributed to the violent epidemic wave, including the lack of immunity of the Haitian population, a lack of access to clean water, sanitation and healthcare, and the fact that the bacterium rapidly proliferated in the optimal environment of the Haitian waters [24]. Although this last point was not supported by any observation or analysis in the field, the speculation linked the epidemic to the theory that prevailed at the time, which was that the cholera outbreak had originated from an environmental source; all but one of the investigators had supported this theory in numerous joint publications with Rita Colwell. Nevertheless, the report concluded that "the Haiti cholera outbreak was caused by the confluence of circumstances as described above, and was not the fault of, or deliberate action of, a group or individual. The source of cholera in Haiti is no longer relevant to controlling the outbreak. What are needed at this time are measures to prevent the disease from becoming endemic" [24].

A few months later, a study conducted by Danish, American and Nepalese researchers provided further evidence that the strain responsible for the epidemic in Haiti was exactly the same as that circulating in Nepal at the time when more than 1000 Nepalese soldiers were about to leave for Haiti after spending ten days on family leave [25]. Although they were traveling to a country with poor WASH infrastructure, which was particularly vulnerable to cholera, they had not been examined or tested upon their return from leave and had not been vaccinated or administered antibiotic prophylaxis against cholera.

4. Continuation and termination of the epidemic

However, an unanswered question regarding the origin of cholera in Haiti remained. Had the disease gone unnoticed by the soldiers, and if so, had the environment acted as an amplifier of the microbial mass that simultaneously infected thousands of inhabitants along the Artibonite Delta? If not, did a cholera outbreak occur among the soldiers that was not reported to the Haitian health authorities? Given the lack of evidence of an outbreak in the military camp, the hypothesis of environmental proliferation of *Vibrio cholerae* was taken for granted. The assumption was also incorporated into the strategy established to fight the epidemic. In a cholera elimination plan written jointly by the Haitian government, the WHO, UNICEF and the CDC, the summary even stated that "because the bacteria are in the environment, sporadic cases will always be detected" [26]. For years, the control strategy essentially consisted in strengthening Haiti's capacity to deal with successive waves of cholera, while efforts to

prevent disease transmission were limited to action plans to improve access to drinking water, sanitation and healthcare in the future. Unfortunately, these expensive plans were not funded. A sum total of $2.2 billion USD was requested from the international community; however, no donors considered such an investment in the fight against cholera in Haiti.

For several years, the fight against cholera in Haiti lacked both a strategic objective and the means to interrupt disease transmission, particularly during the dry season, when control activities could focus during small-scale outbreaks on each individual patient. The Haitian Ministry of Public Health and Population focused its efforts on improving access to health care and limiting the case fatality rate of cholera patients. Since the beginning of the epidemic, several WASH NGOs had been endeavoring (a) to improve access to drinking water by distributing storage containers and water treatment supplies, (b) to improve access to sanitation by encouraging an end to open defecation and supporting the construction and use of latrines and (c) to promote hand hygiene by raising awareness and distributing supplies such as soap. Nevertheless, they operated with little if any coordination, almost blindly, without information regarding the specific location of the areas to be targeted. Furthermore, when disease incidence dropped, rather than attempting to break the transmission cycle by reaching every single case, the response teams tended to scale down their efforts. By early 2013, even though the cholera in Haiti still represented the largest epidemic in the world, disease incidence was relatively low and many NGOs had ceased or were preparing to discontinue their cholera control activities [27]. Donors were satisfied with the relatively sharp decline in incidence. They considered that the disease had become endemic and was thenceforth a development issue rather than an emergency. At the same time, a few pilot mass vaccination campaigns had been implemented or were being prepared in limited areas [28,29], administering an oral cholera vaccine that had recently been prequalified by the WHO and was found to be at best moderately effective.

In this context of strategic disarray, UNICEF agreed to coordinate and fund a nationwide response strategy based on case-area targeted interventions (CATIs) conducted by mobile rapid response teams [30]. This approach, which had been successfully implemented to control polio and Ebola virus disease outbreaks and during a few cholera epidemics in Africa, aims to interrupt disease transmission around newly detected cases as early as possible based on real-time analysis of epidemiological data. This strategy was launched in July 2013 in conjunction with the Ministry of Public Health and Population and the Haitian Drinking Water and Sanitation Directorate.

The ministry's Epidemiology Directorate quickly put in place throughout the country's 140 communes a three-tiered alert system, which was based on weekly analysis of (a) the number of suspected cholera cases and deaths and (b) *Vibrio cholerae* O1-positive stool cultures [31]. The strategy was to direct the mobile teams to cholera treatment centers by means of cholera alerts, the objective being to gather specific information on case localization. Slowly but surely, the ministry established a complementary system through which epidemiological data were shared based on case line lists with addresses, thereby enabling teams to save valuable time in view of implementing targeted response interventions [30].

The first mobile teams were recruited in July 2013 by several NGOs throughout Haiti and contracted by UNICEF. They consisted exclusively of Haitians from the communities, including one or two social mobilizers, a chlorine spraying agent and a driver [30]. In March 2014, the initial teams were joined by mobile teams from the Ministry of Public Health and Population, which also included nurses. Their joint field interventions consisted of visiting the homes and nearby neighbors of all suspected cholera cases, ideally on the same day or the day after admission to a cholera treatment center, the objectives being to search for other suspected cases, to investigate factors favoring transmission, and to raise awareness about the disease itself, about the prevention measures to be taken, and what to do in case of early symptoms. The teams also decontaminated surfaces potentially contaminated with patient feces by spraying a chlorine solution and distributed water treatment supplies (usually chlorine tablets), soaps and adapted water storage containers, if necessary. Team nurses offered single-dose antibiotic prophylaxis of doxycycline to the most at-risk contacts. Finally, the mobile teams coordinated with the Drinking Water and Sanitation Department to repair any broken or dysfunctional water supply and distribution systems.

Implementation of this strategy was not easy, as it was necessary to harmonize and optimize the intervention protocols of each team and, in certain instances, to counteract and overcome local political opposition [30]. Moreover, the available funds often did not suffice to quickly respond to all suspected cases. The situation changed in late 2016 after Hurricane Matthew had devastated the southwestern tip of the country in October, causing many experts to anticipate an increased number of cholera cases. In December 2016, in his annual General Assembly address, UN Secretary General Ban-Ki Moon apologized to the Haitian people: "On behalf of the United Nations, I want to say very clearly: we apologize to the Haitian people. We simply did not do enough with regard to the cholera outbreak and its spread in Haiti. We are profoundly sorry for our role" [32], thereby half-heartedly admitting that UN peacekeepers had been responsible for introducing cholera in Haiti, six years earlier.

Even though the funds requested at the time were never collected, it was henceforth less difficult to consolidate the budget allocated for CATIs and to recruit a larger number of mobile teams for longer periods. With more manpower, the teams could respond to more cases at a faster pace. As a result, cholera incidence dropped sharply in 2017 and even more so in 2018. The last cholera outbreak, the last confirmed case and the last death were observed in February 2019 in the L'Estère commune, in the Artibonite plain, where the epidemic had initially exploded in October 2010 [33].

Subsequent analyses demonstrated that the CATI-based national cholera control strategy was crucial to the eradication of cholera in Haiti [33]. That much said, over the past ten years the living conditions of Haitians have shown little or no improvement, and progress toward increase access to water and sanitation has been highly limited, if not downright non-existent. Only 10% of the population has been vaccinated against cholera, in a majority of cases outside of the most affected regions. Moreover, vaccination campaigns have not been able to compensate for the progressive erosion of the immunity that the Haitian population had acquired during the initial epidemic waves between 2010 and 2012. To date, the potential role that bacteriophages may have played in suppressing *Vibrio cholerae* populations and thereby extinguishing cholera in Haiti remains purely theoretical [33].

5. On the origin of cholera epidemics during the seventh pandemic

The ability to sequence the entire genome of the strain that caused the cholera epidemic in Haiti represented a major advance toward understanding the origin of the epidemic. At the time, rapid sequencing the genome of a bacterium responsible for an epidemic was considered sufficiently innovative to justify an article in the *New England Journal of Medicine* [34]. Since then, many studies have provided significant insight regarding the genesis of the seventh pandemic and the mechanism by which cholera has spread across the globe over the last sixty years. Publications based on whole-genome sequence analysis of a large panel of isolates collected during cholera epidemics have shown that all strains of the seventh cholera pandemic share a common ancestor, which gradually evolved since the first half of the twentieth century [35]. We now know that the emergence of the seventh pandemic in 1961 was the result of a process

spanning more than sixty years, during which an initially non-pathogenic strain spread through the Middle East, acquiring the ability to synthesize cholera toxin, before causing outbreaks in the Makassar region of Indonesia [36]. This causal strain was designated *Vibrio cholerae* O1 El Tor, the name of the lazaretto in Sinai where it was observed for the first time [36]. The strain gradually adapted to humans, thereby gaining the capacity to cause epidemics. The seventh pandemic subsequently unfolded in successive waves, during which the Americas were affected by two large-scale epidemics [37]. The first large-scale outbreak began in 1991 following the importation of two strains in Peru and Mexico, while the second outbreak caused the epidemic in Haiti in 2010. In all three cases, the epidemics were the consequence of transcontinental importation of strains of the seventh pandemic lineage, and not the emergence of a local strain in the environment. Interestingly, a similar process has been demonstrated concerning cholera epidemics in Africa, which have been provoked by at least eleven successive introductions from Asia [38]. Serial introductions and eliminations of epidemic lineages observed both in the Americas and Africa has led experts to question the environmental cholera paradigm and to propose control strategies based on rapid outbreak detection and a targeted response designed to rapidly halt disease transmission [39].

6. Conclusion

Three years after the last signs of epidemic activity in the country, can we talk about cholera elimination in Haiti? The Global Task Force on Cholera Control (GTFCC) brings together various actors from around the globe under the aegis of the WHO in the fight against cholera. The task force has defined cholera elimination as the absence of confirmed community transmission for three consecutive years, as determined by a well-functioning epidemiological and laboratory surveillance system. With no deaths and no outbreaks of suspected cases, and with more than 6,000 *Vibrio cholerae* O1-negative stool cultures collected from diarrhea patients across Haiti since the last confirmed case on February 4, 2019, cholera seems to have finally been eliminated in that country, and the Haitian authorities have celebrated the event. An official certificate of cholera elimination is expected from the GTFCC in 2022.

The nearly decade-long fight against this epidemic provides an opportunity to draw invaluable lessons in view of optimizing cholera control and elimination efforts in other countries. The experience in Haiti demonstrates that CATIs represent an effective means of controlling cholera epidemics. Cholera control strategies based on mobile rapid response teams have since been implemented in Yemen and Mozambique, and an ambitious CATI-based approach is underway in the eastern region of the Democratic Republic of Congo.

The experience in Haiti also demonstrates that theories and paradigms require continuous challenge by field observations. The environmental cholera paradigm was established based on studies almost exclusively conducted in the Bay of Bengal, and which focused on statistical correlations between aquatic environmental data and cholera incidence rates in neighboring population; in these studies, diverse aquatic *Vibrio cholerae* strains were confused with the pandemic *Vibrio cholerae* O1 El Tor clone, which has been circulating and evolving for a century. Over recent years, so we have shown, the theory associating ocean-dwelling *Vibrio cholerae* with the epidemic in Haiti has been debunked by rigorous field epidemiology analyses and molecular epidemiology. From an epistemological point of view, a theory on the origin of cholera epidemics that has proven false should be thoroughly reevaluated. As outlined above, a fundamental change in theoretical framework will have major implications for cholera control strategies on a global scale.

However, many in the scientific community have yet to be convinced. They still refuse to question the environmental cholera paradigm, regardless of the fact that it fails to corroborate observations such as the documented introduction of a Nepalese *Vibrio cholerae* strain in Haiti during a military troop movement or the close phylogenetic links between the different strains collected during the seventh pandemic. As regards the Haitian epidemic, scientists found themselves embroiled in complex interactions with policy-makers who may have had an interest in keeping the possible UN-linked origin of the epidemic under wraps. The scientists were probably misled by the publication of truncated data suggesting that epidemic started in Artibonite River Delta and was caused by environmental strains. The political decision-makers were in turn reinforced in their fallacies by scientific statements that repeated and amplified the refuted information. As a result, the fight against cholera was misdirected for several years by dint of manifestly inappropriate strategies. Public health and the scientific sphere are far from free of conflicts of interest and biases in their reasoning, as observed with cholera in Haiti and, more recently, with regard to the COVID-19 pandemic.

Disclosure of Competing Interest

The authors declare that they have no conflicts of interest

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