Chaos, Solitons and Fractals 168 (2023) 113159

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

journal homepage: www.elsevier.com/locate/chaos

Role of vaccine in fighting the variants of COVID-19

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A R T I C L E I N F O

Keywords:
Vaccine
Effectiveness
Infectivity
Mortality
Singularity width

A B S T R A C T

In this paper, we investigate the effectiveness of COVID-19 vaccination in controlling the infectivity and mortality of the SARS-CoV-2. Two major variants Delta and Omicron are investigated respectively. The main method used in the research is the multifractal detrended fluctuation analysis (MF-DFA). We use $\Delta\alpha$ as the evaluation of control effectiveness. In the transmission stages of Delta and Omicron, we observe whether $\Delta\alpha$ shows a downward trend by gradually expanding the length of time series. Vaccine effectiveness is evaluated using a time series of newly diagnosed patients and newly reported deaths. Data samples are taken from 9 different countries. According to the obtained results, the vaccine controls infectivity and mortality of the virus in the Delta transmission stage, but infectivity control is less effective than mortality. In the Omicron transmission stage, the immune effect of the vaccine is not obvious, which may be related to the high infectivity of Omicron. However, the vaccine is still effective in controlling mortality. We also find that the immune effect of vaccine on Omicron was lower than that of Delta. Finally, we observe that the immune effect of the vaccine in 'Poland' was abnormal. By analyzing the vaccination curve, we conclude that in 'Poland', when the growth rate of vaccination rate slowed down, the immune effect of the vaccine was very poor in terms of pathogenicity and lethality. Therefore, we suggest that all countries should continue to strengthen the vaccination rate. A higher or faster growth rate of vaccination rate will help control the infectivity and mortality rate, especially in the effectiveness of controlling mortality. Our research can be used to evaluate the effectiveness of vaccines for epidemic prevention and control, the formulation of epidemic prevention measures and vaccination policies for different countries with respect to their current pandemic situation accordingly.

1. Introduction

The spread of SARS-CoV-2 has caused over 260 million confirmed cases and more than 5.3 million deaths worldwide, has posed serious threats to global public health and caused significant turbulence on the world economy [1,2]. The development of COVID-19 vaccines has been the major measure to combat the disease. Vaccine development has been the top priority worldwide. By testing the immunogenicity and protectiveness of vaccines in human trials, many candidate vaccines have been proved to be safe and effective, and have been vaccinated on a global scale since early 2021 [3,4]. The rate of vaccination showed an overall upward trend, as of December 2021, a total of 8.5 billion doses of vaccines have been vaccinated worldwide.

However, since the outbreak of COVID-19 pandemic, the original strain continues to produce new variants in the process of continuous transmission. Among many variant strains, the influential ones include the Delta variant [5–8] found in India in October 2020 and Omicron variant [9–11] first reported to World Health Organization by the South African government in November 2021. The Delta variant contains a total of 15 mutations, and the Omicron variant has more mutations than the Delta virus strain, carries at least 32 mutations. A large number of mutations mean that it may weaken the efficacy of the existing COVID-19 vaccine and may be more infectious. Will this weaken the vaccine's protection for humans? Lipsitch and Dean [12] thought that although the availability of a COVID-19 vaccine would initially be limited, having reliable evidence on protection could help the expert committees how to use these in vaccines in a coordinated way. Due to the confirmed cases even could appear in vaccinated populations, and based on the previous clinical trials, the myriad vaccine-induced mechanisms had demonstrated adverse effects. In this case, Kostoff et al. [13] explored that under an accelerated schedule, whether short, mid, and long-term vaccine safety can be ensured. COVID-19 vaccine is an important tool, but they must be used effectively and in combination

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https://doi.org/10.1016/j.chaos.2023.113159
Received 21 September 2022; Received in revised form 29 December 2022; Accepted 16 January 2023
Available online 18 January 2023
0960-0779/

with other evidence-based public health measures in order to play a decisive role [14,15]. In addition, other scientific issues about vaccines, such as vaccine manufacturing, safety, protection effectiveness, coordinated supply and fair distribution, have also been widely discussed in [16–23].

Nevertheless, the rapid growth trend of the cases confirmed by the COVID-19 worldwide has not slowed down even though the global vaccination rate is climbing. Virus infection occurred even in people who had received the third strengthen dose. Are existing COVID-19 vaccines ineffective? The vaccination rate is not high enough? Does the vaccine provide 100% prevention? At present, there is no evidence at the data level.

To fill this gap, we investigate the nonlinear physical phenomena behind the virus transmission from the time series of the number of newly diagnosed patients and the number of newly dead patients every day, and mine the protective effect of the vaccine from the data level. The main method is the multifractal detrended fluctuation analysis method (MF-DFA) [24]. Multifractal method is an effective method to study the dynamic characteristics of nonlinear time series, which has been used in various disciplines [25–33]. For studying the nonlinear characteristics of the time series of daily new cases of COVID-19, Wang et al. [34] employed the MF-DFA to reveal the nonlinear characteristics of the time series of daily new patients, and then discussed the effect of "Wuhan closure" on the COVID-19 pandemic in China.

In this study, according to the time point of vaccine output of each country, and the vaccination rate of the vaccine, we utilize different control groups to explore the nonlinear physical characteristics of the daily number of new patients and the daily number of new deaths between countries with different COVID-19 vaccination rates. Due to the wide application in nonlinear time series, MF-DFA is adopted in this paper to explore the characteristics of daily new patients and daily new deaths. As well, according to [34], it is reasonable to apply MF-DFA to reveal the embodiment of the effectiveness of the vaccine on the current global anti-epidemic effect and the impact of the vaccination rate on the daily number of new patients and the daily number of new deaths, and investigate whether the vaccine can resist the spread of SARS-CoV-2 virus variants.

The remainder of the paper is structured as follows. We introduce the methodology in Section 2. Section 3 presents the data information. Section 4 contains the empirical results. Section 5 reports the conclusion.

2. Methodology

Multifractal Detrended Fluctuation Analysis (MF-DFA) studies the multifractal process on the basis of DFA. This method can accurately quantify the long-term correlation of non-stationary time series, and has become an important tool to study non-stationary time series.

We consider a non-stationary time series X_i of length N, $i = 1, 2, \dots, N$. Construct a new time series by definition, i.e., a cumulative series of the deviations of the original series from their mean. Where, μ_x represents $\frac{1}{N}\sum_{i=1}^{N} x_i$.

$$y_i = \sum_{j=1}^{i}(x_j - \mu_x), i = 1, 2, \dots, N. \tag{1}$$

Divide y_i into $N_s = [N/s]$ non-overlapping small intervals. Each interval contains s pieces of data. Since the total length of the given data is not necessarily a multiple of s, in order not to lose a small part of the sequence left by the split, our approach is to do the same split at the end of the sequence y_i to obtain $2N_s$ segments.

A polynomial fit is performed on the series for each segment using the least squares method to obtain the local trend for each segment. The fitting order here should be chosen in an appropriate order to prevent overfitting or underfitting. And calculate its mean square error $F^2(v, s)$. Let $y(v)$ be the fitted polynomial for the v unit interval.

$$F^2(v,s) = \begin{cases} \frac{1}{s}\sum_{i=1}^{s}\{Y[(v-1)s+i] - y(v)\}^2, & if\ v = 1, \dots, N, \\ \frac{1}{s}\sum_{i=1}^{s}\{Y[N-(v-N_s)s+i] & \\ -y(v)\}^2, & if\ v = N_s+1, \dots, 2N_s. \end{cases} \tag{2}$$

Calculating the mean of $2N_s$ segments, obtain the q order wave function $F_q(s)$ as

$$F_q(s) = \left\{ \frac{1}{2N_s}\sum_{v=1}^{2N_s}[F(s,v)]^{q/2} \right\}^{\frac{1}{q}}. \tag{3}$$

When $q = 0$, according to Lopida's law,

$$F_q(s) = exp\{ \frac{1}{2N_s}\sum_{v=1}^{2N_s} ln[F^2(s,v)]\}. \tag{4}$$

$F_q(s)$ is a function of segment s and fractal order q. With the increase of s, the series are long-range power-law correlated, and the generalized Hurst exponent $h(q)$ is defined by $F_q(s) \propto s^{h(q)}$, when $q = 2$, $F_q(s)$ is the standard DFA.

When the original sequence is monofractal, the scales of variance $F^2(s, v)$ in each segment s are constant, therefore, $h(q)$ is a constant independent of q. The generalized Hurst exponent $h(q)$ can be obtained by finding the slope of the $F_q(s)$ curve in the log–log plot. The range of $h(q)$ indicates the extent to which the series is multifractal. A higher $\Delta h = h(q_{min}) - h(q_{max})$ means stronger multifractal feature.

In addition, we can give a multifractal scale exponent $\tau(q)$ that depends on h_q, and if $\tau(q)$ satisfies the smoothing condition, the singular strength α is as follows. Similarly, $f(\alpha)$ can be constructed by the Legendre transform [35]. The multifractal degree can also be described between the singularity strength α and the fractal dimension $f(\alpha)$. According to [24], the fractal strength $\Delta\alpha$ can reflect the degree of multifractal complexity.

$$\tau(q) = qh(q) - 1, \tag{5}$$

$$\alpha = \tau'(q) = h(q) + qh'(q), \tag{6}$$

$$f(\alpha) = q[\alpha - h(q)] + 1, \tag{7}$$

3. Data collection

In this paper, the dataset is downloaded from "https://ourworldindata.org", including the number of new infections per day, the number of new deaths per day, and the proportion of vaccinations per 100 people. The time frame is from March 9, 2020 to April 5, 2022. The countries selected for analysis are all over the world, from different races. Meanwhile, the samples also reflect the differences in vaccination rates and vaccination increase rates between countries. The samples of the countries include 'India', 'Russia', 'Colombia', 'Poland', 'Indonesia', 'Netherlands', 'South Africa', 'United Kingdom', and 'Germany'. In this study, we focus on the two main variants of COVID-19, Delta variant and Omicron variant. We examine how well the vaccine confers protection against transmission of the mutant strain, and whether the vaccine prevents patients from becoming severely ill or dying. The data used in the time series is the number of new diagnoses and deaths per day. We plot the trend of vaccination rates in these nine countries in Fig. 1.

In the variation process of SARS-CoV-2, the two main variants Delta and Omicron appeared in October 2020 and November 2021, respectively. Dating from the time series data from the beginning of 2021 to November 2021 can reflect the control effect of the vaccine on Delta variant. The interval of the initial time series is 2020/03/09–2021/06/26, with a total of 474 data. Then, the vaccination information is slowly reflected by increasing the sequence length. Moreover, we change the interval of the time series, and every 9 days are added to the later date until 2021/11/09 (i.e. the date of emergence of Omicron variant). In this way, we can get 16 time series for multifractal analysis.

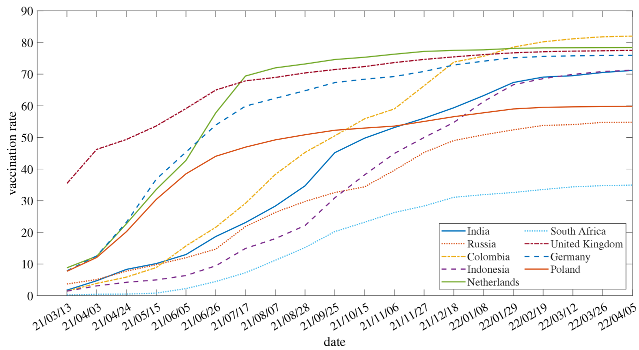

Fig. 1. Rend chart of vaccination rate. A color version of the figure is available in the web version of the article.

Table 1
Time series intervals for analyzing the effectiveness of vaccination on Delta variant transmission control.

1	2020/03/09–2021/06/26	9	2020/03/09–2021/09/06
2	2020/03/09–2021/07/05	10	2020/03/09–2021/09/15
3	2020/03/09–2021/07/14	11	2020/03/09–2021/09/24
4	2020/03/09–2021/07/23	12	2020/03/09–2021/10/03
5	2020/03/09–2021/08/01	13	2020/03/09–2021/10/12
6	2020/03/09–2021/08/10	14	2020/03/09–2021/10/21
7	2020/03/09–2021/08/19	15	2020/03/09–2021/10/30
8	2020/03/09–2021/08/28	16	2020/03/09–2021/11/08

Table 2
Time series intervals for analyzing the effectiveness of vaccination on Omicron variant transmission control.

1	2020/07/23–2021/11/09	9	2020/07/23–2022/01/20
2	2020/07/23–2021/11/18	10	2020/07/23–2022/01/29
3	2020/07/23–2021/11/27	11	2020/07/23–2022/02/07
4	2020/07/23–2021/12/06	12	2020/07/23–2022/02/16
5	2020/07/23–2021/12/15	13	2020/07/23–2022/02/25
6	2020/07/23–2021/12/24	14	2020/07/23–2022/03/06
7	2020/07/23–2022/01/02	15	2020/07/23–2022/03/15
8	2020/07/23–2022/01/11	16	2020/07/23–2022/03/24

As the coverage time closer to 2021/11/09, the vaccination rate would become higher with wider coverage and more sufficient nonlinear dynamic characteristics of the number of newly diagnosed patients and deaths per day caused by Delta variant by the vaccination environment. Similarly, in order to reflect the control effect of the vaccine on Omicron variant, we select the interval of the initial time series from 2020/07/23 to 2021/11/09, and the length is still 474 data. Then, the data of 9 days will be added to the later date, until 2022/03/24, which also contain 16 time series for analysis, and reflect the change degree of the control effectiveness of the vaccine for Omicron variant. In the analysis of Delta variant and Omicron variant, the selected periods of time series are shown in Tables 1, and 2.

The calculations in this study are handled by MATLAB R2020a on an Intel(R) Core(TM) i5-4430 CPU 3.00 GHz processor.

4. Computational results

4.1. Examination of multifractality

In this section, we use MF-DFA method to confirm whether all time series have multifractal characteristics. We take the daily new patients time series and daily new deaths time series for the Delta variant as examples to explore the multifractality. According to $F_q(s) \propto s^{h(q)}$, we can achieve the generalized Hurst exponent $H(q)$. In this paper, q increases from -10 to 10 in steps of 2, thus the number of q is 11. Here, the interval size s varies from [5, 61] in step of 1. We plot the images of the double logarithm curves of fluctuation equation $F_q(s)$ in Fig. 2 where the top line represents the $ln(F_q(s))$ when q equals 10 and the bottom one represents the value when q equals -10. The slope of the line is the $H(q)$. The variety of q affects the slope which becomes small when q increases. Therefore, the daily new patients time series for Delta variant can be proved that it owns multifractal behavior.

Subsequently, we calculate the generalized Hurst exponent, the scaling exponent and multifractal spectrum of the daily new patients time series for Delta variant, respectively. According to the double log plot, the generalized Hurst exponent $H(q)$ represents the slope of a double log curve. Since the number of points on the double log curve is too huge, we take the first as an example. The generalized Hurst exponent $H(q)$ of daily new patients time series for Delta variant is presented in Fig. 3. It is obvious to observe that $H(q)$ varies with q in Fig. 3 which proves that the time series is multifractal. The calculated Hurst exponent $H(q)$ decreases obviously before $H(q)$ increases to 0. Meanwhile, $H(q)$ is much more than 0.5, suggesting the remarkable persistence of small fluctuations. Fig. 4 exhibits the conditions of the scaling exponent $\tau(q)$. Similar to $H(q)$, the scaling exponent $\tau(q)$ alters with q as well.

Based on α, q and $H(q)$, $f(\alpha)$ can be obtained. Fig. 5 displays the multifractal spectrum $f(\alpha)$. Except United Kingdom, the multifractal spectrum curves of the other eight countries are unimodal convex functions, which can further imply that the experimental time series has multifractal characteristics.

Nextly, we analyze the multifractality of the daily new deaths time series for Delta variant. In the previous calculations, we accumulate the sequence once. However, when the sequence is regular, the cumulate summation is unnecessary. In Russia, Colombia, Poland, Netherlands and South Africa, daily new deaths time series for Delta variant are relatively regular, indicating that the accumulation step is unnecessary. Therefore, when analyzing the multifractality of the five countries, we delete the cumulative summation. The range of q still goes from -10 to 10 in steps of 2. Considering that some time series are relatively regular, the cumulative summation is not adopted, thus, the scope of s has been adjusted as well. When studying daily new deaths time series for Delta variant, the scope of s for Russia, Colombia, Poland and Netherlands is [15, 61], and the range of s in South Africa is [25, 61]. The range of s in other countries is still [5, 61].

Fig. 6 exhibits log–log plots between $F_q(s)$ and s of the initial time series of daily new deaths time series for Delta variant. We find that the slope still varies with q, which prove that daily new deaths time series has multifractal behavior. Especially in the second half of the curve, the fluctuation is more intense. As well, we find that the slope decreases quickly when q increases to 0. When q becomes positive, the variety of the slope becomes slow which is consistent with the variation of the generalized Hurst exponent $H(q)$.

Fig. 7 displays the generalized Hurst exponent $H(q)$. It is obvious that $H(q)$ exhibits a downward trend, proving that daily new deaths time series for Delta variant owns multifractal nature. Compared with the double log plots of Russia, Poland, Netherlands, and South Africa, we find that when q increases, the slopes of the double log curve are a little similar. However, observing $H(q)$, it decreases as q increases.

The scaling exponents $\tau(q)$ of daily new deaths time series for the Delta variant about different countries are calculated based on q and $H(q)$ which are presented in Fig. 8. We find that $\tau(q)$ increases with the increasement of q except Russia, Colombia, Poland, Netherlands, and South Africa. When calculating the scaling exponent, the cumulative summation is not adopted in the time series about the five countries.

Fig. 9 presents the multifractal spectrum of the initial time series. No matter in which country, $f(\alpha)$ is smaller than 1. Each $f(\alpha)$ is a unimodal convex function, indicating that daily new deaths time series for Delta variant is multifractal.

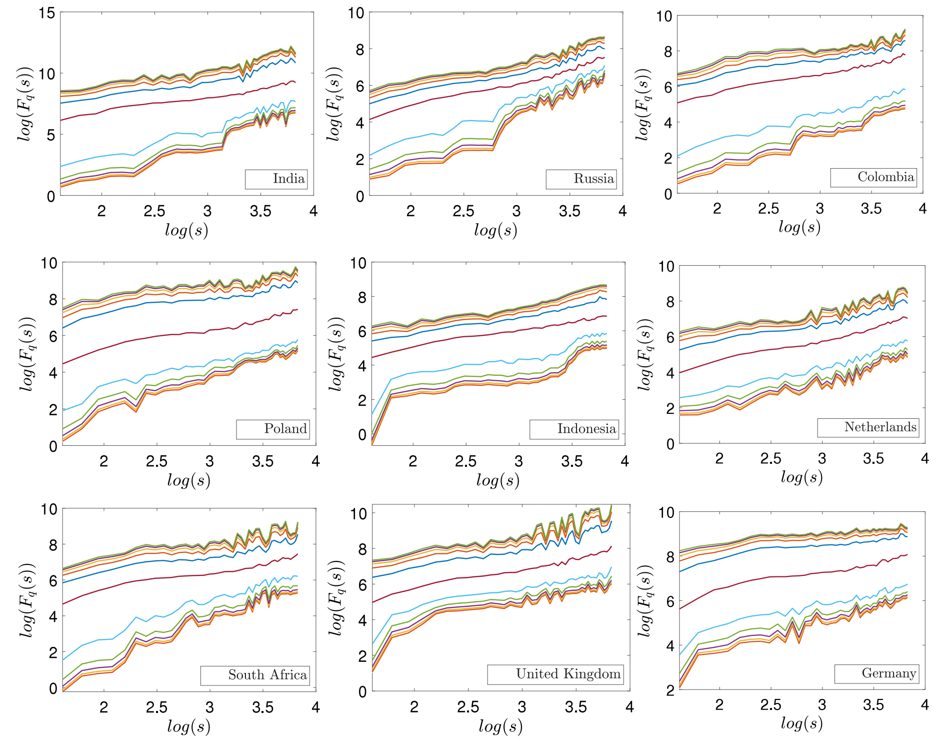

Fig. 2. Double log plots between s and $F_q(s)$ of the initial time series of daily new patients time series for Delta variant. From the bottom to the top are $-10, -8, \ldots, 8, 10$, respectively.

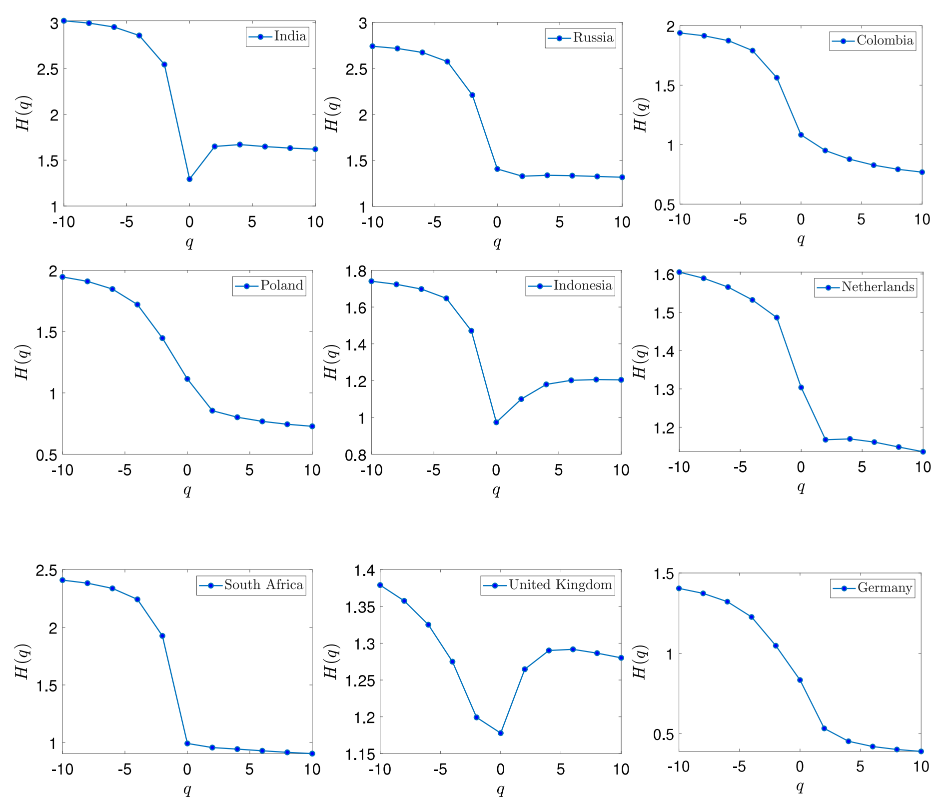

Fig. 3. Generalized Hurst exponent of the initial time series of daily new patients time series for Delta variant.

4.2. Analysis of the vaccine in fighting the variants

Afterwards, we calculate the singularity strength α and the fractal dimension $f(\alpha)$ for each time series interval, where α and $f(\alpha)$ are calculated by q. From these, we derive the fractal complexity degree $\Delta\alpha$, which is also a common indicator used to analyze the effectiveness of financial markets. According to [36,37], the multifractal feature is negatively correlated with market efficiency. Therefore, a higher $\Delta\alpha$

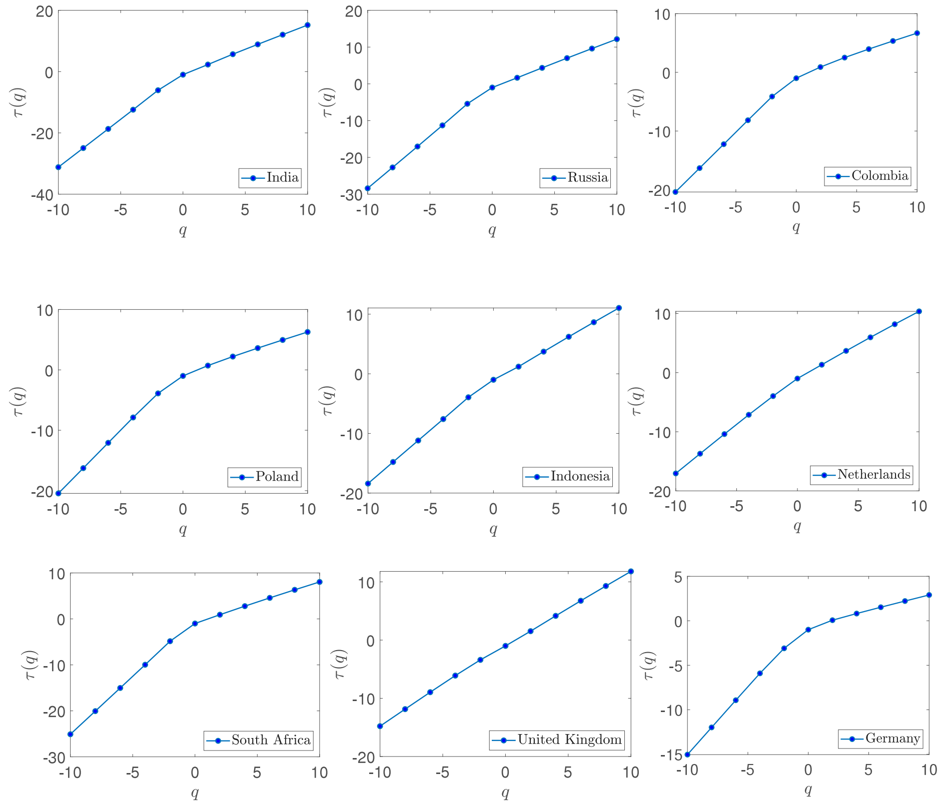

Fig. 4. Scaling exponent of the initial time series of daily new patients time series for Delta variant.

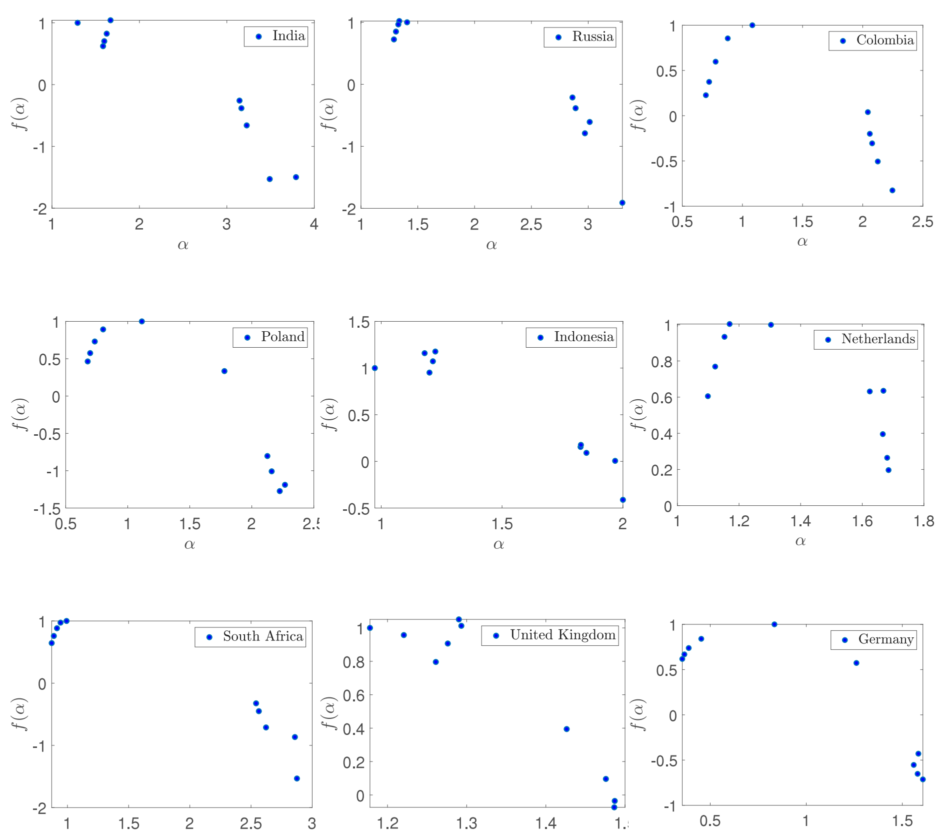

Fig. 5. Multifractal spectrum of the initial time series of daily new patients time series for Delta variant.

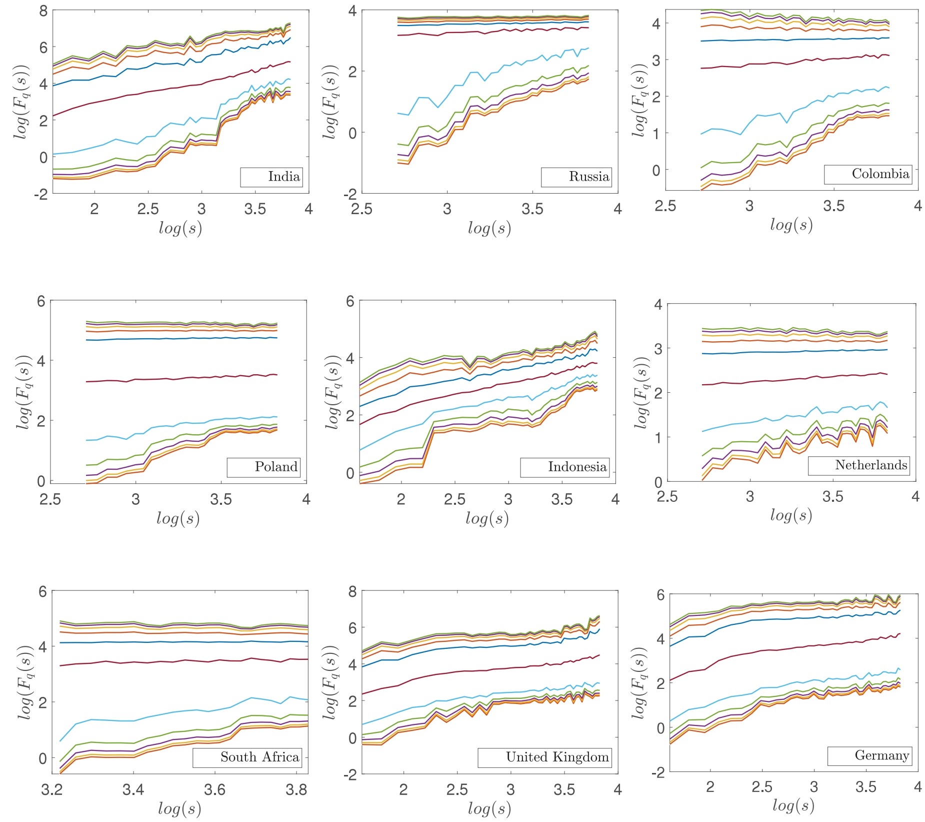

Fig. 6. Double log plots between s and $F_q(s)$ of the initial time series of daily new deaths time series for Delta variant. From the bottom to the top are $-10, -8, \ldots, 8, 10$, respectively.

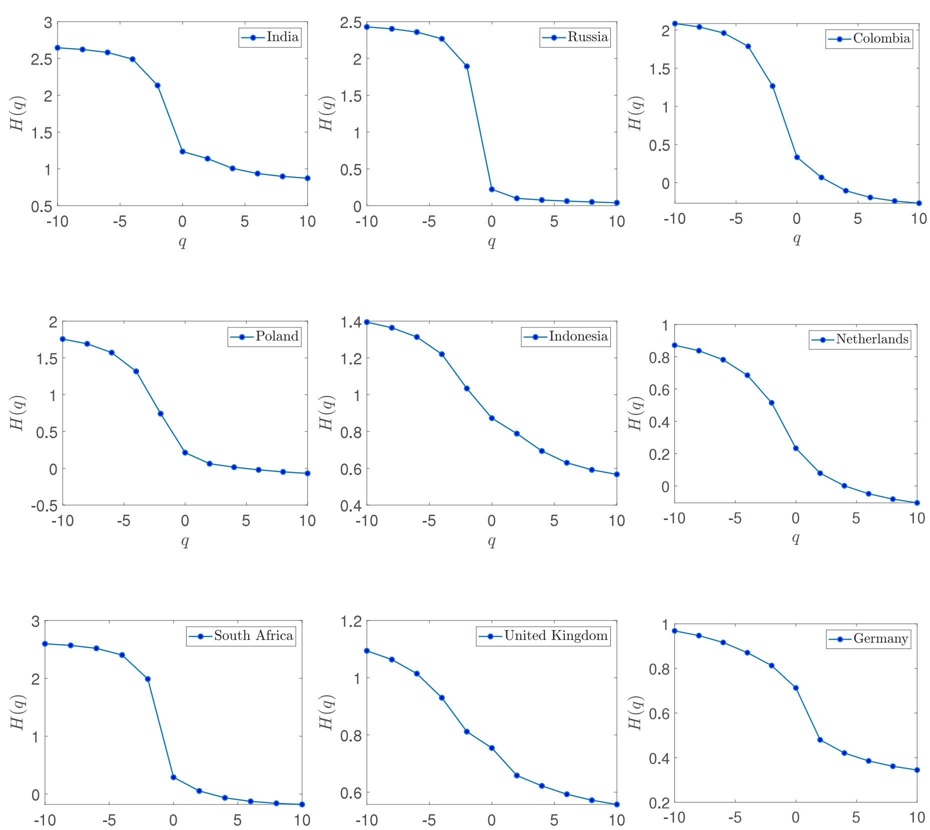

Fig. 7. Generalized Hurst exponent of the initial time series of daily new deaths time series for Delta variant.

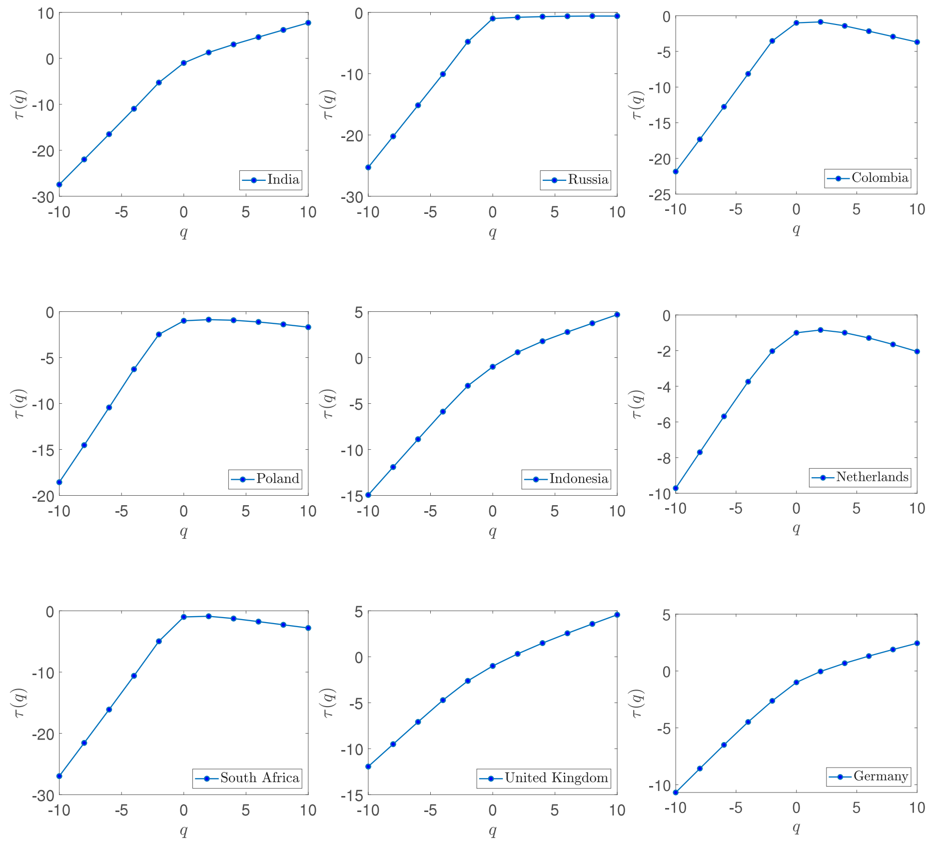

Fig. 8. Scaling exponent of the initial time series of daily new deaths time series for Delta variant.

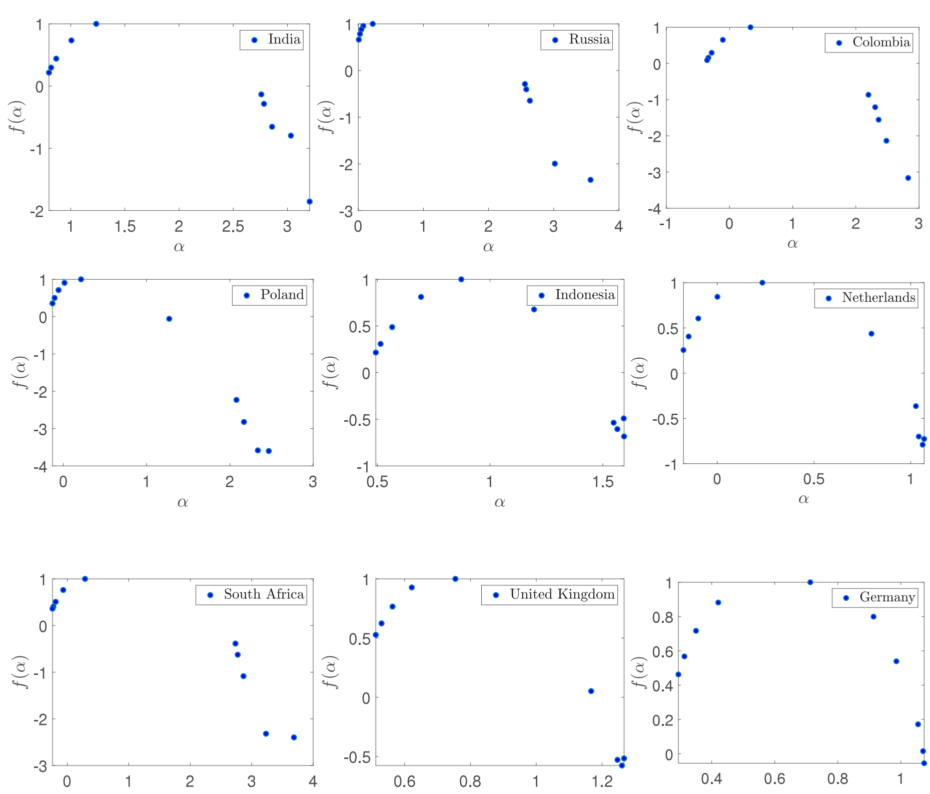

Fig. 9. Spectrum of the initial time series of daily new deaths time series for Delta variant.

indicates a less efficient market. In the previous literatures [38,39], which using MF-DFA to analyze the effectiveness of financial markets, $\Delta\alpha$ is often utilized as an index to judge the strength and weakness of the market effectiveness brought by the shock event. If $\Delta\alpha$ becomes larger, it implies that the shock event weakens the effectiveness of the financial market that currently analyzed, and vice versa.

In this research, the objects are the time series composed of daily new patients and daily new deaths. Since the prevention and control measures for COVID-19 in various countries remain unchanged, vaccination as a variable under the epidemic period, we investigate the immune effect of the vaccine, according to the change of fractal complexity degree $\Delta\alpha$ of the time series. Then observe whether the vaccine has the ability to prevent patients from turning into severely ill or even death. In addition, during the COVID-19 pandemic, there are several key time points, namely "Delta occurrence time", "vaccination start time", and "Omicron occurrence time". Since the vaccination start time is after the emergence of Delta, in this article, we only take the time point of Omicron as the sensitive analysis point, and then the similarities and differences of the transmission of the two strains are analyzed and compared. At the same time, considering that the two time series data representing virus infectivity and mortality are used in the article, we can also draw a comparison of the efficiency of vaccine in controlling virus infection and mortality in people during the transmission of Delta variant and Omicron variant.

We first evaluate the impact of the vaccine during the transmission of strain Delta. Since the vaccination rates of the selected sample countries are rising continuously, we gradually expand the time range of time series to evaluate whether the efficiency of vaccines is instrumental in controlling the transmission of Delta strain, and expand the range until the day before the occurrence of Omicron. Through the calculation of the time series of new infected cases and new death cases in the MF-DFA model for all the 9 countries, we draw the changes of the effectiveness (i.e. $\Delta\alpha$) trend of the vaccine in controlling virus infectivity and lethality in these 9 countries with the increase of the coverage period of continuous vaccination, as shown in Figs. 10 and 11. The number corresponding to the abscissa in the figures refers to the time period of the time series used to calculate the multifractal features, please refer to Table 1.

As shown Fig. 10, the longer the time period covered by the time series, the smaller the value of $\Delta\alpha$ is in most countries, which indicates that with the increasing vaccination rate of the vaccine, the control effectiveness of the vaccine in the time series of controlling the number of new patients is increasing. We fitted the chart of countries with obvious downward trend with a black straight downward line. In addition, there are no similar phenomena in four countries such as 'Indonesia', 'Netherlands', 'United Kingdom', 'Germany', which indicates that the effectiveness of vaccination in controlling Delta transmission is not obvious in these countries, which may also be related to the epidemic prevention policies of these countries. Furthermore, Fig. 11 behaves that in the time series of daily new deaths, with the expansion of the range, the values of $\Delta\alpha$ in 9 countries show a downward trend, indicating that the vaccination is able to control the mortality rate under Delta transmission. Moreover, according to Figs. 10 and 11, the advantages of vaccination in controlling the severity and mortality caused by Delta variant are significantly better than those of vaccine in controlling the population infected with Delta variant, which is similar to the reality phenomenon [40]. In terms of controlling the spread of the virus, the control effect of several countries is not significant. However, in terms of controlling lethality, the effectiveness of the vaccine continues to improve in all countries.

Though there is no theory of the singularity width in vaccine validity, it is an effective tool for describing the nonlinear time series. Considering that the singularity width is commonly adopted in financial markets, and the daily new patients and daily new morality are nonstationary time series, it is reasonable to apply the method to the evaluation of the effectiveness of the vaccine. From a statistical point of view, the calculated results demonstrate that for so many countries, the effectiveness of the control of mortality shows a downward trend in general. Different from the mortality, the results of controlling the daily new patients do not present a downward trend. Gupta et al. [41] found that the vaccine is effective for Delta variant which reduces the amount of the death in the US. Meanwhile, the percentage of vaccinated patients is negatively correlated with the number of deaths per million and case fatality rate of COVID-19. Although it seems that vaccination cannot reduce the risk of COVID-19 infection, it can significantly reduce mortality [42–44]. The experimental results are consistent with the medical researches.

It is worth noting that the Omicron variant was found on November 9, 2021. Will the new variant weaken the protective efficiency of the vaccine? Next, we take November 9, 2021 as the key time point and gradually increase the coverage of the time series. From November 9, we add 9 days of data to the later time each time until March 24, 2022. Similarly, we calculate the $\Delta\alpha$ of new confirmed cases and new death cases time series using MF-DFA. The changes of the effectiveness trend of the vaccine in controlling virus infectivity and lethality in these 9 countries are exhibited in Figs. 12 and 13. The numbers corresponding to the abscissa in figures are described in Table 2.

All $\Delta\alpha$ in Fig. 12 do not show a significant downward trend, that is, due to the daily number of new patients used in Fig. 12, the effectiveness of the vaccine on the immune ability of people infected with Omicron virus has not been strengthened, and this phenomenon occurs in all countries, which is different from that of Delta variant. On the one hand, this may be due to the increased infectivity of Omicron. On the other hand, from Fig. 1, we preserve that after the emergence of Omicron, the growth rates of vaccination rate in all countries drop moderately, or even tend to remain unchanged. By comparing Figs. 10 and 12, we can also conclude that the transmission of Omicron variant is stronger than that of Delta variant, since the protective effect of the vaccine is decreasing. In addition, we also analyze the time series of daily new deaths. As shown in Fig. 13, $\Delta\alpha$ in all countries except 'Poland' shows a downward trend. We observe that the vaccine still has the effect of controlling the mortality under the Omicron variant. Therefore, all countries in the world should continue to promote vaccination. Even in the process of continuous variation of the virus, the infectious capacity of the virus continues to increase. Damijan et al. [45] have proved that vaccines were quite effective in limiting the spread of infection and preventing more serious disease progression in symptomatic patients. Meanwhile, the necessity of COVID-19 vaccination should be adequately disseminated which can increase public acceptance of the vaccine, thereby increasing the vaccination [46]. In addition, the effectiveness of public health messaging strategies and public trust in government have significant impact on the vaccination acceptance [47]. However, vaccination can effectively control the severe rate, then the effectiveness of controlling mortality continues to increase. This is also the evidence provided by the empirical results calculated from the perspective of nonlinear dynamics in the data, and combined with statistical methods.

Considering that nonlinear correlations may be the main reason for the possible existence of intrinsic multifractals, a statistical test is adopted in this paper. Drozdz et al. [48] found that the multifractality of time series might be caused by the nonlinear correlations appeared in the results. However, in financial returns, the linear correlation or not of the temporal structure have a smaller influence on the singularity width $\Delta\alpha$ [37]. For more analysis of multifractals in the financial field, please refer to [49]. Interestingly, Gao et al. [50] demonstrated that not all the grain indices owned multifractal behaviors.

We take the daily new patients time series for the Delta variant about India, Colombia and South Africa as examples. At first, we randomly disrupt the time series. Subsequently, MF-DFA is adopted to calculate the multifractal spectrum and singularity width of the time series. Afterwards, we utilize phase Fourier randomization to scramble the original time series and use MF-DFA to analyze them. $f(\alpha)$ and

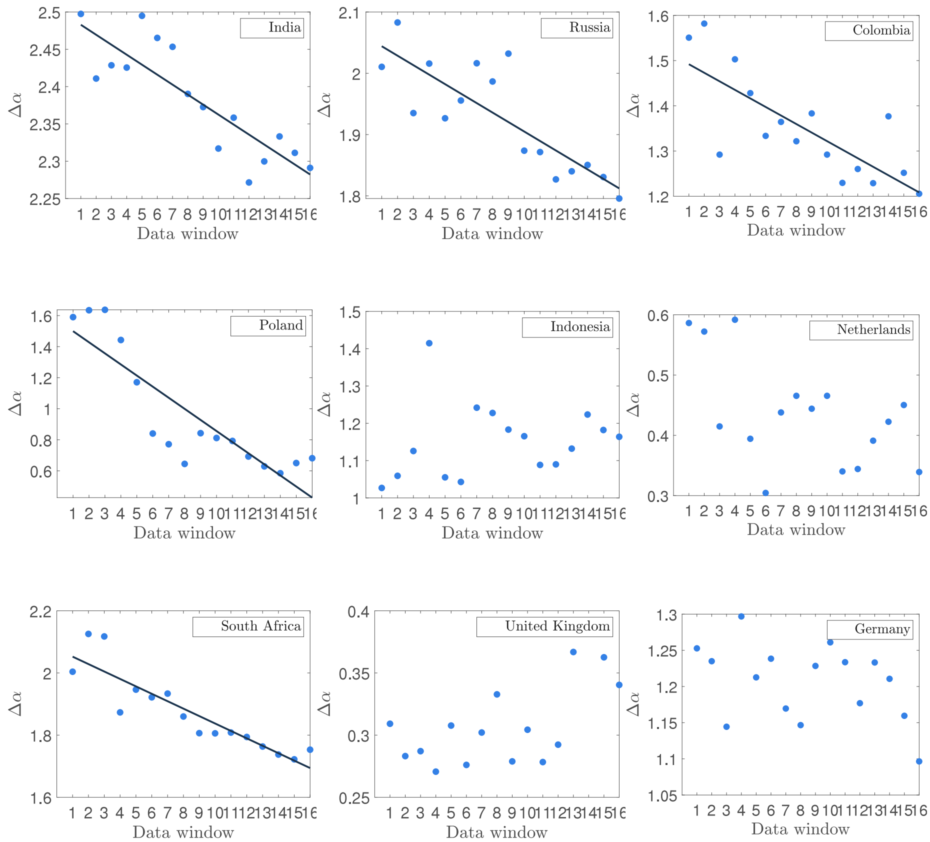

Fig. 10. Trend chart of $\Delta\alpha$ with the increasing coverage of daily new patients time series for Delta variant. A color version of the figure is available in the web version of the article.

$\Delta\alpha$ are used to examine the effect of the nonlinear correlation to the multifractality.

The singularity width of the original and disturbed time series are exhibited in Fig. 14. We find that the trend of $\Delta\alpha$ are similar of the three time series, implying that the change of data position has little impact on the trend of $\Delta\alpha$. When the given time series is merely disturbed, $\Delta\alpha$ is generally smaller than the original one. When using phase Fourier randomization, the difference of $\Delta\alpha$ between the upset time series and the original time series is small which even can be ignored.

Fig. 15 shows the multifractal spectrum of daily new patients time series for the Delta variant about India, Colombia, and South Africa. It is obvious that when the time series is marginally disturbed, the multifractal spectrum curve becomes narrow and the peak value is unchanged. Meanwhile, the curve of multifractal spectrum, which is marginally disturbed time series, is obviously shifted to the left. As well, the unimodal convex function is more obvious, indicating that the simply disarranged time series is multifractal. In addition, we use phase Fourier randomization to upset the time series. The multifractal spectrum of the upset time series is similar to the original time series. Therefore, the time series which is upset by phase Fourier randomization owns multifractality as well.

In addition, we notice that in Fig. 13, the situation in Poland is relatively special, and the effectiveness of vaccines in controlling the number of deaths is not obvious. By observing the vaccination data, as shown in Fig. 16(a), by April 6, 2022, the vaccination rate in 'Poland' is close to 60%. Firstly, the vaccination rate is not high. Although the vaccination rates in 'Russia' and 'South Africa' are lower than those in Poland, the epidemic prevention and control are also related to the prevention and control policies of different countries. Rzymski et al. [51] pointed out that vaccine hesitancy caused by trust in vaccine had a significant impact on vaccination rates. Meanwhile, general public knowledge and awareness of the COVID-19 vaccines in Poland were insufficient at that time [52]. However, by observing the vaccination curve in 'Poland', we point out that after the emergence of Omicron variant (i.e. after November 9, 2021), the increase of vaccination rate in 'Poland' was relatively slow, the increase momentum of vaccination rate was insufficient, and even there was almost no substantial increase in vaccination rate for a long time. Since in this period of time, which is the stage of rapid transmission of Omicron variant, the low vaccination rate is difficult to effectively prevent and control the infectivity and mortality of Omicron strain. In addition, we re-examine the effectiveness of vaccines in preventing and controlling infectivity of Delta variant for 'Poland' in Fig. 16(b). We find that after the data window 8, that is, after August 28, 2021, $\Delta\alpha$ has no obvious downward trend. Corresponding to Fig. 16(a), the period from August 28, 2021 to November 9, 2021, we note that the vaccination rate curve during this period is also relatively flat, while the downward trend of $\Delta\alpha$ before data window 8 is obvious. By comparing the curve from March 13, 2021 to August 28, 2021 in Fig. 16(a), it is witnessed that the vaccination rate increased rapidly. It can be concluded that in 'Poland', continuously improving the vaccination rate can effectively control the virus mortality rate, and it is more sensitive to vaccination under the current epidemic prevention and control policy in 'Poland'. Therefore, we suggest that 'Poland' should vigorously advocate people to get vaccinated in order to increase its vaccination rate.

5. Conclusions

In this study, we adopted the MF-DFA method to calculate the fractal complexity $\Delta\alpha$ for the time series of daily new confirmed cases and daily new deaths. The selected sample includes 9 countries from different continents in the world. These 9 countries have a certain

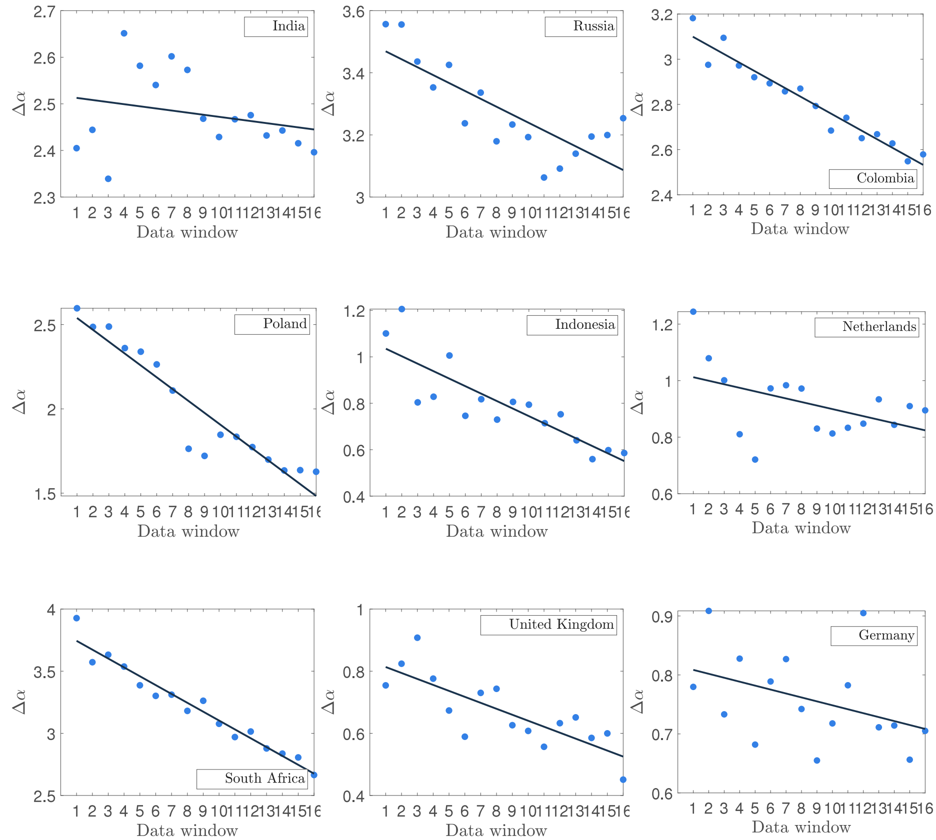

Fig. 11. Trend chart of $\Delta\alpha$ with the increasing coverage of daily new deaths time series for Delta variant. A color version of the figure is available in the web version of the article.

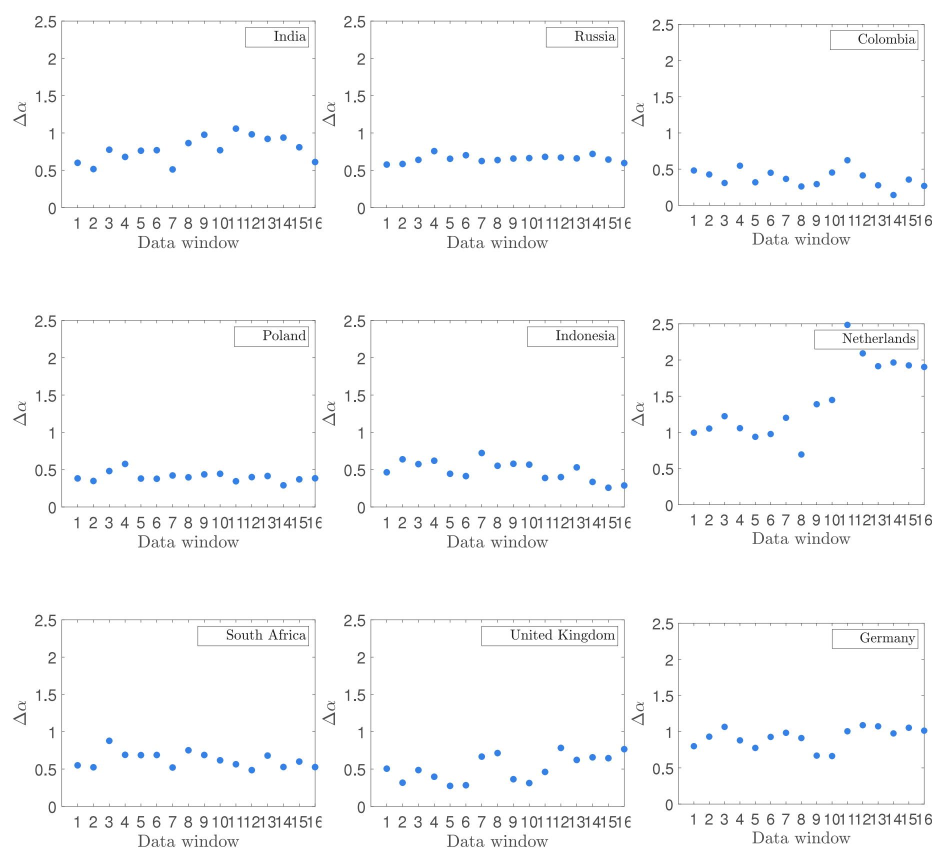

Fig. 12. Trend chart of $\Delta\alpha$ with the increasing coverage of daily new patients time series for Omicron variant.

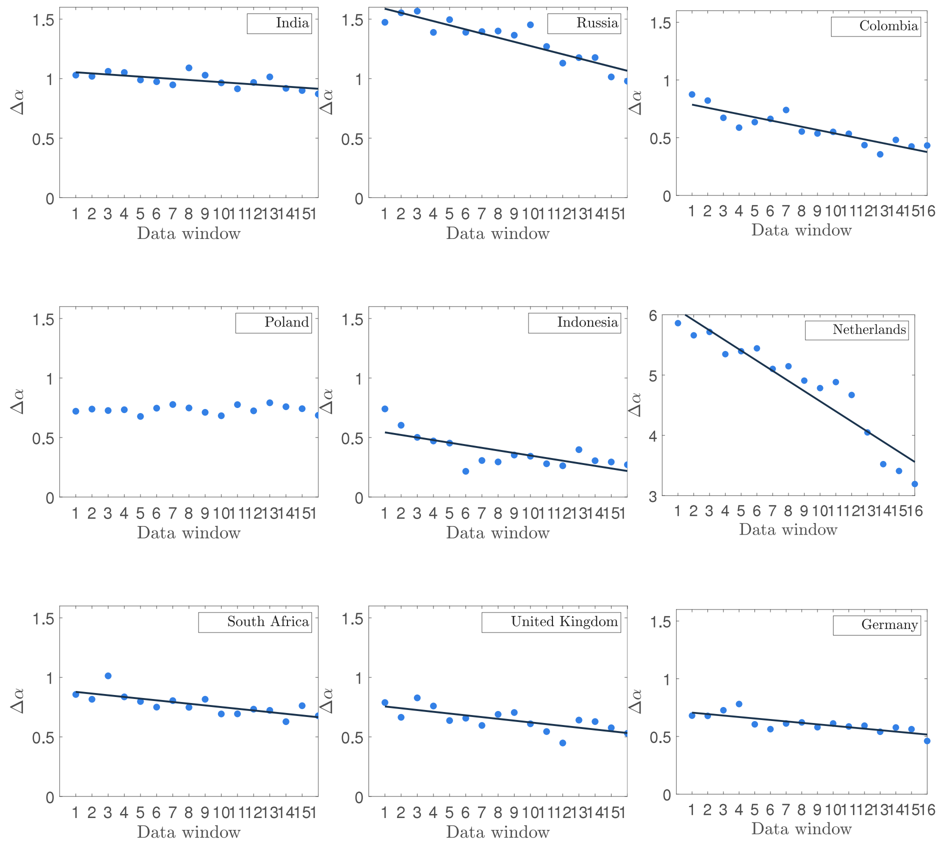

Fig. 13. Trend chart of $\Delta\alpha$ with the increasing coverage of daily new deaths time series for Omicron variant. A color version of the figure is available in the web version of the article.

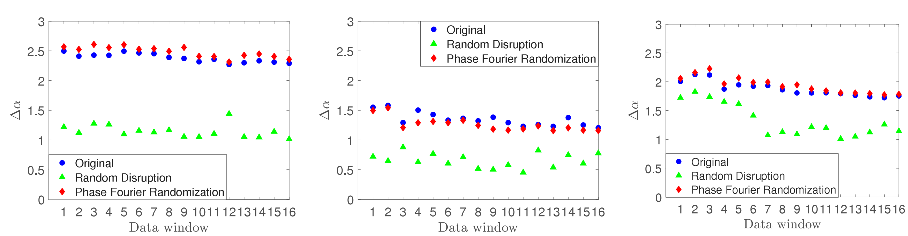

Fig. 14. Trend chart of $\Delta\alpha$ with the increasing coverage of daily new patients time series for Delta variant about India, Colombia and South Africa. From left to right, the country is India, Colombia, and South Africa.

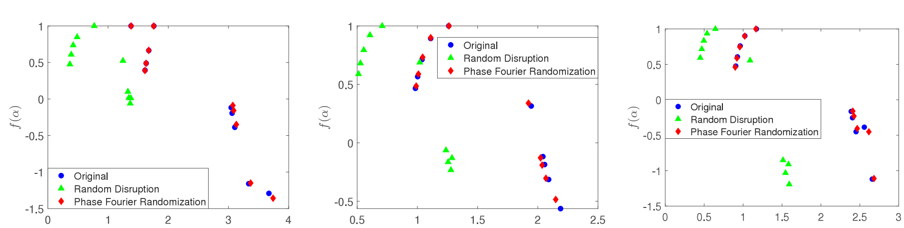

Fig. 15. Multifractal spectrum of daily new patients time series for Delta variant about India, Colombia, and South Africa. From left to right, the country is India, Colombia, and South Africa.

vaccination rate, and the vaccination data are different. Our research focused on comparing the effectiveness of the vaccine in controlling the morbidity and mortality in the vaccination environment, and the similarities and differences of the immune ability of the two main variants of COVID-19 in transmission.

$\Delta\alpha$ can be used to perceive the effectiveness. In the process of increasing the coverage of time series, we observed whether the $\Delta\alpha$ of each country gradually decreases with the expansion of the coverage of time series. This phenomenon can explain the immune effect of the vaccine under the transmission of corresponding variants. Our calculation results showed that the vaccine is effective in preventing and controlling the new patients under the Delta variant in some countries, but it is effective in preventing and controlling the new deaths in all 9 countries. After the virus mutated into Omicron, the infectivity of Omicron was further enhanced. The effectiveness of the vaccine in preventing and controlling new patients under Omicron variant was

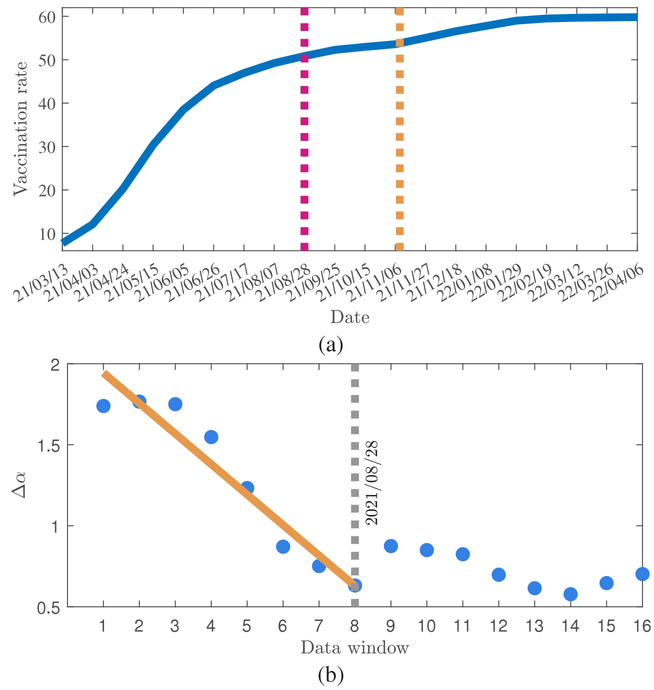

Fig. 16. (a) Trend chart of vaccination data in 'Poland', and (b) trend chart of $\Delta\alpha$ with the increasing coverage of daily new patients time series for Delta variant in 'Poland'. A color version of the figure is available in the web version of the article.

not obvious in all 9 countries, but it was effective in preventing and controlling new deaths in 8 countries except 'Poland'. We also analyzed the reasons for this situation in 'Poland'. The analysis results showed that when the vaccination rate increased rapidly in 'Poland' at the beginning, which was in the period of Delta transmission. At that time, it was effective for controlling both new patients and new deaths under the Delta variant. As the vaccination rate plummets, although it still had an effect on controlling the mortality under the Delta variant, it was inefficient to control the infectivity. After the emergence of Omicron variant, the effectiveness of the vaccine in controlling both morbidity and mortality was not obvious in 'Poland'. Therefore, we suggest that 'Poland' should maintain a high vaccination rate to combat Omicron variant. We hope that our research can provide governments with the right amount of inspiration for controlling epidemics and formulating vaccination strategies.

CRediT authorship contribution statement

Jian Wang: Methodology, Writing, Coding. **Wenjing Jiang:** Writing, Reviewing. **Xinpei Wu:** Writing, Reviewing. **Mengdie Yang:** Writing, Reviewing. **Wei Shao:** Supervision, Data collection, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The first author Jian Wang expresses thanks for the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (Grant Nos. 22KJB110020). The corresponding author (Wei Shao) was supported by Jiangsu shuangchuang project (JSSCBS20210431). The authors would like to thank the reviewers for their comments regarding the revision of this article.

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