ORIGINAL RESEARCHES

Predicting the dynamics of Covid-19 incidence and planning preventive vaccination measures for Moscow population based on mathematical modeling

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The results of the predictive analytical studies on Covid-19 incidence dynamics in Moscow, taking into account different changes in epidemic prevention measures, including vaccination coverage of the population, are presented.
Research Objective. Using the new epidemiological model for analysis and prediction of the Covid-19 incidence dynamics in Moscow and outlining main strategies in implementing epidemic prevention measures (EPMs), including vaccination in 2020/2021.
Materials and methods. The epidemiological model is based on the Russian approach to mathematical modeling of epidemics, known as Epiddynamics. The medium-term forecasting incorporated probable scenarios of epidemic development with different EPMs (isolation of the infected and contacts, breaking the transmission chains), including different rates of vaccination coverage in Moscow.
Results and discussion. The computational simulations demonstrated that the incidence rate is likely to increase with scaling down EPMs and zero vaccination coverage. At the same time, the daily incidence rate depends on the degree of EPMs reduction and basically does not depend on the time when the reduction begins. With scaled-down EPMs, vaccination can decrease the incidence, though its effectiveness will depend on the time of its commencement, coverage and rate.
Conclusion. The computational simulations showed that the vaccination will be efficient for prevention of new surges in COVID-19 cases only if the other EPMs (isolation of the infected and contacts, breaking the transmission chains) are still in place until the vaccination coverage reaches about 2 million people. Ideally, the measures aimed at isolation and breaking of transmission chains should be continued until the total vaccination coverage reaches 4 million people, after which the restrictive measures can be scaled down significantly. With vaccination coverage of 50% of the population of Moscow, the restrictive measures can be completely discontinued.

Keywords: *Covid-19, SARS-CoV-2, epidemic process, epidemiological model, potential scenarios, epidemic prevention measures, predictive analytical studies.*

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Прогнозирование динамики заболеваемости COVID-19 и планирование мероприятий по вакцинопрофилактике населения Москвы на основе математического моделирования

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Введение. Распространение вируса SARS-CoV-2 продолжается во всем мире. Большие надежды возлагаются на вакцины, которые разрабатываются во многих ведущих научных центрах мира, в том числе в России.
Цель исследования — с помощью разработанной эпидемиологической модели провести анализ и прогноз динамики заболеваемости COVID-19 на территории Москвы и определить основные подходы к организации противоэпидемических мероприятий (ПЭМ) с учетом вакцинации населения на сезон 2020/2021 гг.
Материалы и методы. Эпидемиологическая модель разработана на базе отечественной теории математического моделирования эпидемий «Эпиддинамика». Прогнозную оценку на среднесрочный период проводили на основе прогнозных сценариев развития эпидемической ситуации при различных изменениях ПЭМ (по изоляции инфицированных и контактных лиц, прерыванию механизма передачи), в том числе с учетом различных объемов вакцинации населения Москвы.
Результаты и обсуждение. Вычислительные эксперименты показали, что существует вероятность подъема заболеваемости при ослаблении ПЭМ в отсутствие вакцинации населения. При этом высота пика ежедневной заболеваемости зависит от степени снижения ПЭМ и практически не зависит от времени начала их снижения. Проведение вакцинации на фоне ослабления ПЭМ позволяет снизить заболеваемость, однако степень влияния зависит от времени начала, объема и скорости охвата населения вакцинацией.
Заключение. Результаты вычислительных экспериментов показали, что для предотвращения значительного подъема заболеваемости COVID-19 на фоне проводимой вакцинации необходимо поддерживать остальные ПЭМ до достижения объема охвата вакцинацией около 2 млн человек. Оптимальным представляется сохранение мер по изоляции и прерыванию механизма передачи до достижения суммарного объема охвата вакцинацией 4 млн человек, после которого возможно значительное ослабление ограничительных мер; при охвате вакцинацией 50% населения Москвы возможна их полная отмена.

Ключевые слова: *COVID-19; SARS-CoV-2; эпидемический процесс; эпидемиологическая модель; прогнозные сценарии; противоэпидемические мероприятия; прогнозно-аналитические исследования.*

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Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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Dedicated to the memory of Boris Vasilievich Boev

Rationale

The problem of the emergence of epidemics and pandemics of infectious diseases and the search for preventive measures will never lose their relevance. The head of the Laboratory of Epidemiological Cybernetics at the Gamaleya Research Institute of Epidemiology and Microbiology, D. Eng. Sci. B.V. Boev wrote in 2005: "According to forecasts, in the first half of this century, anywhere in the world, one should expect an epidemic or an outbreak of both "new" and "old" infectious diseases. In this context, advanced scientific studies on the analysis and forecasting of probable scenarios for development of epidemics of dangerous infectious diseases that may occur as a result of natural and man-made emergencies are of particular importance" [1].

After an outbreak of pneumonia had been reported in Wuhan in December 2019, the novel coronavirus quickly spread across all countries and continents. By early August 2020, the number of recorded SARS-CoV-2 cases exceeded 18 million people, with the death toll reaching more than 688 thousand fatalities caused by the coronavirus. In Russia, due to the epidemic prevention measures, we were able to curb the spread of the virus; however, according to official statistics, by the beginning of August 2020, more than 850 thousand of SARS-CoV-2 cases and 14 thousand deaths had been reported in Russia. In the meantime, the true number of people who have been infected with the virus far exceeds the number of reported cases. The proportion of unidentified infected people, according to various studies, can range from 11.6% to 35.8% [2–5].

The SARS-CoV-2 virus continues its global spread. We have great expectations for vaccines that are being developed at leading research centers around the world, including Russia[1,2]. The new vaccine against coronavirus developed at the Gamaleya National Center for Epidemiology and Microbiology has successfully passed the clinical trials; its manufacturing is scheduled for September 2020, and then it will be available for vaccination of the population.

The use of an appropriate epidemiological model makes it possible to "recover" data on the incidence, and, by using them, to perform computational simulations of various scenarios of the epidemic situation. It seems relevant to conduct predicative and analytical studies based on the mathematical model of the spread of SARS-CoV-2 and to select the most reasonable scenarios of epidemic prevention measures (EPMs), including vaccination of the population (through the example of Moscow).

Materials and methods

The new epidemiological model incorporated data from the published studies on clinical features, pathogenesis and epidemiology of Covid-19, statistical data on the reported Covid-19 cases and deaths in Moscow over the observation period[3] as well as census data on the population of Moscow (12.678 million people)[4].

The new deterministic mathematical model is based on the Epiddynamics approach incorporating patterns of infection process development (among individuals) to get an insight into the dynamics of the epidemic process in the population [6]. The Epiddynamics approach was successfully used in mathematical modeling and analysis of the spread of significant infectious and non-infectious diseases [7–11]. We used a SEIRF type model as a basis to study the infection dynamics in individuals going through different phases: susceptible (S), exposed (or the incubation period) (E), infected (I), recovered (R) or fatal (F). For modeling, the estimated duration of the phases was as follows: the incubation period after exposure 2–14 days, the clinical (infectious) stage 7–14 days [12].

The probability of an individual's moving to the next stage is set by the functions: $\gamma(\tau)$ is the function of the incubation period; $\delta(\tau)$ is the function of infection development. The mathematical model of epidemic development is presented as a system of nonlinear integro-differential equations in partial derivatives with initial and boundary conditions [1]. The model has been successfully verified with statistical data on morbidity (with consideration of "recovered" data, ref. to section 1). The model disregards seasonal variations in the virus virulence. In addition, it was assumed that the virus did not significantly mutate during the 2020/2021 season. The potential scenarios were developed with consideration for a new vaccine and 70% immunological efficacy.

The research was carried out in several stages:

1. Recovery of data on the Covid-19 incidence and selection of the baseline scenario;

2. Predictive and analytical studies, including:

2.1. Analysis and prediction of the current epidemic situation (according to the baseline scenario);

2.2. Computational simulations based on the potential scenarios.

At the final stage, the obtained results were interpreted and conclusions were made.

Results and discussion

Recovery of incidence data and selection of a baseline scenario

The existence of asymptomatic and mildly symptomatic cases being a distinctive feature of the novel coronavirus infection contributes to the transmission of infection in the population [13]. While severe and moderately severe cases are recorded in clinics and hospitals, patients with mild or absent symptoms may not seek help. Prior to the large-scale sero-epidemiological studies, only a small proportion of asymptomatic cases was identified through epidemiological contact tracing [14]. Thus, the number of reported cases is only a tip of the iceberg, and the complete picture is required for correct interpretation of the epidemic situation. Therefore, the first stage of our research was focused on computations and recovery of the source data.

The data on Covid-19 incidence among the population of Moscow were recovered by two parameters, which were compared later:

1) by estimating upper and lower bounds in mortality from Covid-19 (Infection-Fatality Rate),

2) by estimating the immune stratum of the Moscow population through the analysis of the representative sample.

The infection-fatality rate (IFR) was estimated through the systematic review of the reference literature and the meta-analysis of research results obtained by G. Meyerowitz-Katz and L. Merone [15]. Unlike the CFR (the case fatality rate), which is the ratio between the number of deaths and the number of reported (detected) cases, IFR is calculated as the ratio between the number of deaths from infection and the number of all

[1] Official website of the Ministry of Health, COVID-19 in Russia. URL: https://covid19.rosminzdrav.ru (reference date 20.07.2020).
URL: https://covid19.rosminzdrav.ru/mihail-murashko-17-vakczin-protiv-koronavirusa-pokazali-sebya-kak- perspektivnye/ (reference date 20.07.2020).

[2] WHO. COVID-19 Strategy Update. 20.05.2020. URL: https://apps.who.int/iris/bitstream/handle/10665/332159/WHO-2019-nCoV-Framework_Mass_Vaccination-2020.1-rus.pdf (reference date 20.07.2020).

[3] Stopkoronavirus.rf. Reports of the Communication Center of the Government of the Russian Federation on the situation with the coronavirus URL: https://стопкоронавирус.рф/info/ofdoc/reports (reference date 20.07.2020)

[4] Federal State Statistics Service. URL: https://gks.ru (reference date 20.07.2020).

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infected people (including asymptomatic and mildly symptomatic cases of infection). The IFR in European countries averaged 0.64% at a confidence interval (CI) of 0.50–0.78% [15].

The data on mortality in Moscow from the Emergency Operations Center correspond to the number of deaths due to Covid-19[5]. In accordance with international guidelines for the certification and coding of Covid-19 as a cause of death[6], the source data were recalculated with consideration for the cases when the SARS-CoV-2 virus had a significant impact on the development of fatal complications of the disease[7,8].

The calculations based on the data[9] showed that in April, the number of deaths totaled 850 + 360 = 1,165 cases; in May, the number of deaths was 2,757 + 980 = 3,737 cases. Since the number of deaths in March was several times lower than in April and May (without breakdown by the cause), 24 death cases recorded in the statistical reports of the Emergency Operations Center were taken for calculations. Thus, from the date of official registration to June 1, 2020, the number of deaths totals 4,926 cases.

Based on the number of deaths by June 01, 2020 (4,926 cases), we performed calculations, using the model, to find the ratio between the number of detected cases and the number of "recovered" cases, where the calculated (model) number of deaths by June 1 will be close to 4,926. For the upper bound of the mortality rate (IFR 0.78%), the ratio between the detected (reported cases) and the "recovered" cases is approximately 25% or 1 : 4. For example, by June 1, 2020 the cumulative incidence is 718,687 cases according to the model, and 183,088 cases according to official statistics. For the lower bound of the fatality rate (IFR 0.50%), the ratio between the detected (reported cases) and the model-based "recovered" cases is approximately 16% or 1 : 6. For example, the cumulative incidence by June 1, 2020 is 1,134,836 cases according to the model, and 183,088 cases according to official statistics.

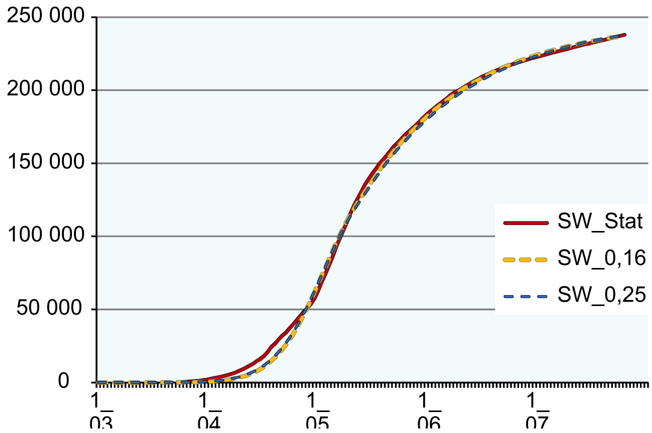

Fig. 1. The result of model verification is a comparison of models (SW_0,16; SW_0,25) and statistical data on cumulative morbidity (detected cases, SW_Stat).

Here and in Figs. 2–9: the horizontal axis shows the dates; the vertical axis shows the number of cases.

The curve of the verified cumulative incidence (detected cases) for two calculation examples (1 : 6 and 1 : 4) matches the curve of official statistics (**Fig. 1**).

The next stage required for well-grounded selection of the baseline scenario from two verified scenarios included the analysis of the antibody test results obtained during the randomized sample studies, which were performed in Moscow from May 15 to May 23, 2020. According to official sources and press service of the Moscow government, SARS-CoV-2 neutralizing antibodies were found in 12.5% of the city's population[10] [16].

Taking into account the specificity and sensitivity of the test systems, the proportion of the infected population was estimated. For this purpose, the possible false-positive cases amounting to 3.8% were subtracted from the declared portion of 12.5%, and then, the false-negative cases amounting to 0.2% were added, representing 8.9% of Moscow population, or 1,130 thousand people[11]. This estimate is close to the calculated ratio between the detected cases and "recovered" cases, which is 1: 6 (at 0.50% IFR).

Thus, for further studies, the scenario with the mortality rate of 0.50% was chosen as the baseline or C0 scenario. **Figures 2 and 3** show the graphs of the model and statistical data on the recorded daily and cumulative incidence.

Based on the calculations, the ratio between the detected cases and the "recovered" cases was 1 : 6.

[5] Official website of the Ministry of Health, COVID-19 in Russia. URL: https://covid19.rosminzdrav.ru URL:https://static-1.rosminzdrav.ru/system/attachments/attaches/000/050/527/original/27052020_MR_STAT_1.pdf (reference date 20.07.2020).

[6] WHO. COVID-19 - GUIDELINES FOR DEATH CERTIFICATION AND CODING.20.04.2020. URL: https://www.who.int/classifications/icd/Guidelines_Cause_of_Death_COVID-19-20200420-RU.pdf?ua=1 (reference date 20.07.2020).

[7] Official website of the Ministry of Health, COVID-19 in Russia. URL: https://covid19.rosminzdrav.ru. URL: https://mosgorzdrav.ru/professional/covid-19 (reference date 20.07.2020).

[8] WHO. Media briefing on #COVID19 with @DrTedros. 10.06.2020. URL: https://twitter.com/WHO/status/1270739116078981120 (reference date 20.07.2020).

[9] Natural movement of the population in the context of the constituent entities of the Russian Federation in January-May 2020. URL: https://rosstat.gov.ru/storage/mediabank/yjmHZnUV/edn05-2020.htm (reference date 20.07.2020).

[10] Official portal of the Mayor and the Government of Moscow. Immunity to coronavirus is formed in 12.5%. URL: https://www.mos.ru/news/item/74512073/ (reference date 20.07.2020).

[11] SARS-CoV-2 IgM. URL: https://keul.de/wp-content/uploads/2020/04/IFU-SARS-CoV-2-IgM-CLIA-1.0.pdf (reference date 20.07.2020).

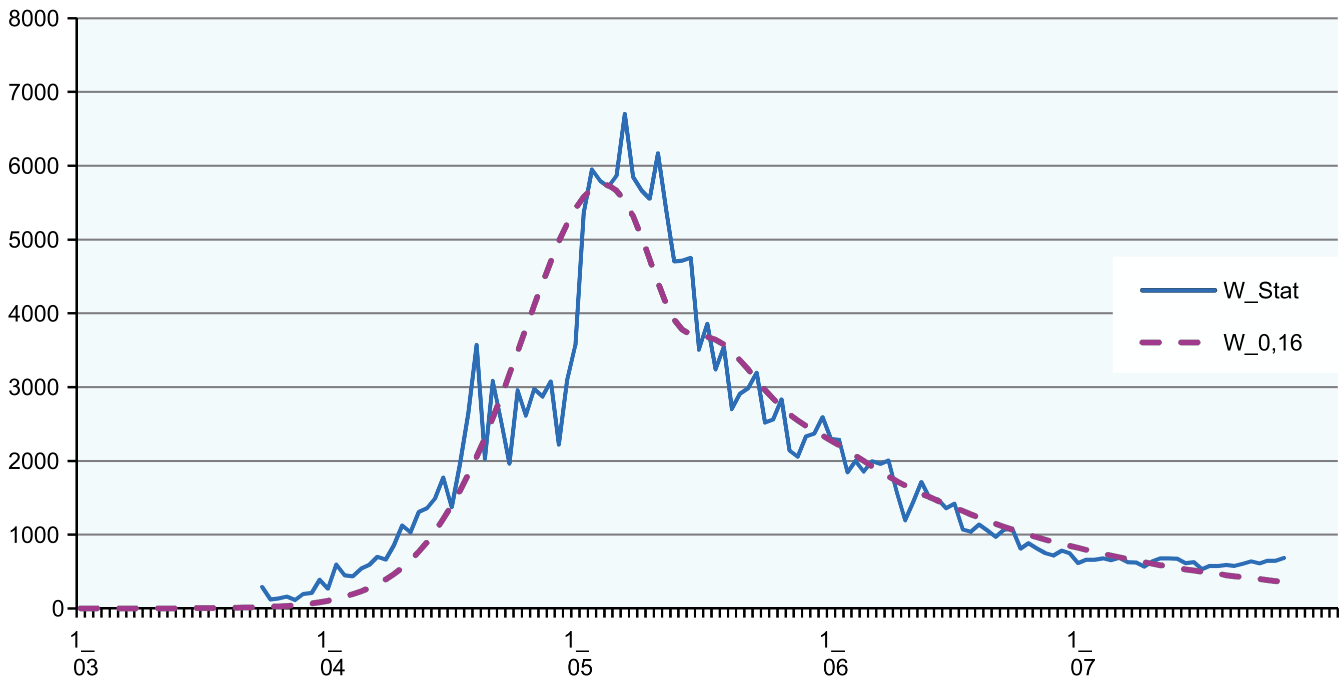

Fig. 2. Detected (reported) cases of daily incidence.
Statistical data — W_Stat, model — W_0,16.

Figure 4 shows the modeling of the dynamics of the "recovered" cumulative incidence and the graph of the detected (reported) cases for reference. The further studies were based on the "recovered" data for the baseline scenario C0.

Predictive and analytical studies

Analysis and prediction of the current epidemic situation according to the baseline scenario (scenario 1 : 6)

The use of a mathematical model allows us to play out (by using the computer) various scenarios of epidemic development, making it possible to answer two questions: "What will happen if…" and "what would happen if…". The last question is also useful, as it helps evaluate the measures taken by the healthcare system and compare the current situation with a hypothetically probable scenario for the epidemic development without the implemented measures.

Figure 5 shows the graphs of daily incidence without preventive measures (red line) and with the implemented EPMs. As can be seen in Fig. 5, the timely implemented measures for isolation of the infected (including self-isolation of the population) and social distancing significantly reduced the daily incidence (approximately by 25 times) and saved thousands of lives.

The analysis of the model parameters showed that for the baseline C0 scenario, EPMs implemented by June 12, 2020 resulted in the following: the isolation reached 67% (the proportion of all infected (contagious) people); measures aimed at breaking the chains of transmission (hygienic precautions at all socially significant facilities, social distancing, wearing face masks

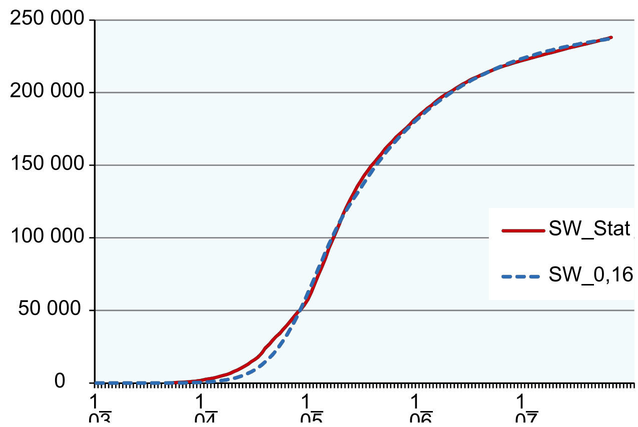

Fig. 3. Detected (reported) cases of cumulative incidence.
Statistical data — SW_Stat, model — SW_0,16.

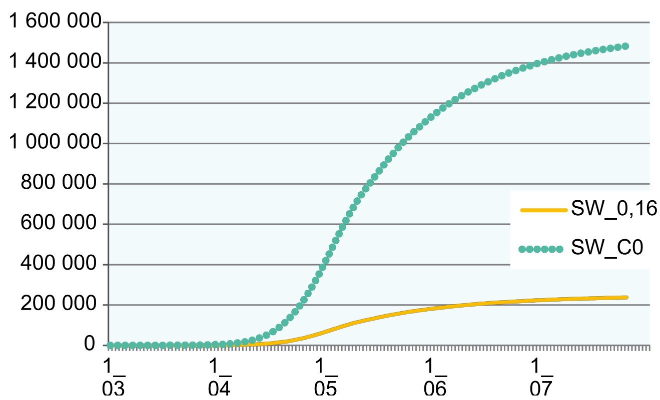

Fig. 4. Detected (reported cases) (SW_0,16) and «recovered» cumulative incidence in accordance with the selected baseline scenario C0 (SW_C0).

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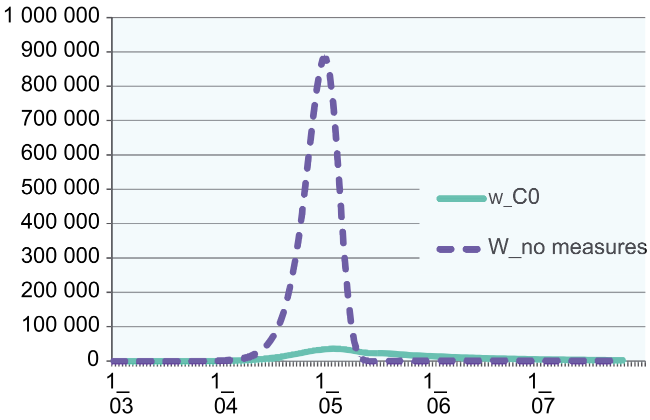

Fig. 5. Comparison of the current daily morbidity (W_C0) and the hypothetical (without measures, W_no measures).

and gloves, personal hygiene) reduced the probability of virus transmission to 14% of its maximum value (the probability of transmission before adoption of the restrictive measures). Taking into account the elimination of restrictions (while retaining social distancing and mask wearing) and expecting an increase in business activity in September, we assumed a slight (and gradual) EPM reduction from June 12 to September 25, 2020[12,13]. The date of September 25, 2020 is selected randomly as the probable commencement of vaccination among the population of Moscow[14]. Provided that the level achieved by September 25, 2020 due to the prevention measures remains stable in the future, the daily incidence will decrease, comprising singular cases after January 2021 (**Fig. 6**). The cumulative number of the infected can total 1.558 million, and the cumulative number of deaths will not exceed 8 thousand according to this scenario.

The C0 scenario shows that if the adopted EPMs remain effective for a long time, the incidence can stay at a fairly low level. But what will happen if measures are scaled down when the incidence rate is low? To answer this question, we performed computational simulations under the scenarios presented below.

Computational simulations under potential scenarios

To reduce and prevent the spread of infection, the main EPMs should be aimed at 3 factors (drivers) of the epidemic process: The source of infection (isolation of contagious patients), transmission of infection (breaking the chain of infection through different measures, including hygiene preventive measures in public spaces and social facilities, social distancing, wearing face masks and gloves, improved personal hygiene), and susceptible individuals (routine vaccination, emergency preventive care)[15] [17]. Before the new vaccine was developed, the main measures were focused on two factors — source of infection and transmission chains. The model shows that timely adopted restrictive measures helped significantly reduce the disease incidence (Figure 5).

The successful clinical trials of the new Russian vaccine with participation of volunteers add confidence in planning of the measures including vaccination of the population. Can EPMs be scaled down? What coverage and rate of vaccination are required? Under what conditions can the measures be reduced without causing a surge in Covid-19 cases? To answer these questions, we prepared potential scenarios of development of the Covid-19 epidemic situation, taking into account different changes in EPMs and various ranges of vaccination coverage of the Moscow population (the vaccination commencement on September 25, 2020). In addition, we conducted computational simulations with the model (**Table 1**).

The EPM reduction levels are shown in the table as slight, moderate and significant, in percentage terms:

- Slight (insignificant) reduction in measures — reduction by 2% from the level achieved by June 12, 2020;
- Moderate reduction in measures — reduction by 13% from the level achieved by September 25, 2020;
- Significant reduction in measures — reduction by 50% from the level achieved by September 25, 2020.

Potential scenarios with different levels of reduction in EPMs without vaccination of the population

The modeling results for potential scenarios C1.0, C2.0, and C3.0 (without vaccination) are shown in **Fig. 7.**

Scenario C1.0 illustrates the situation when there are only a few isolated cases of the disease (or no cases may be recorded by the end of February) and seasonal ARVI (acute respiratory viral infection) incidence goes down, the restrictive measures will be eliminated, for example, starting from March 2021, which means a sig-

[12] Methodological Guidelines of 08.05.2020 MR 3.1.0178-20 «Determination of a set of measures, as well as indicators that are the basis for the phased lifting of restrictive measures in the context of the epidemic spread of COVID-19». URL: https://www.rospotrebnadzor.ru/upload /MP_поэтапное%20снятие%20огранич._08.05.2020.pdf (reference date 20.07.2020).

[13] Sergey Sobyanin's website. Return to normal life. Educational, theater, cinema and children's entertainment centers. URL: https://www.sobyanin.ru/otmena-ogranicheniy-obrazovanie-i-detskie-tsentry (reference date 20.07.2020).

[14] A moderate reduction in measures and vaccination commencement from 25.11. 2020 show similar simulation results.

[15] Methodological Guidelines MR 3.1.0170-20. Epidemiology and Prevention of COVID-19 (read with MR 3.1.0175-20, Amendment No. 1 in MR 3.1.0170-20, Epidemiology and Prevention of COVID-19, approved by Rospotrebnadzor on 30/4/2020). URL: https://www.rospotrebnadzor.ru/upload/iblock/070/metod_recomend_3.1.0170_20_v_1.pdf (reference date 20.07.2020).

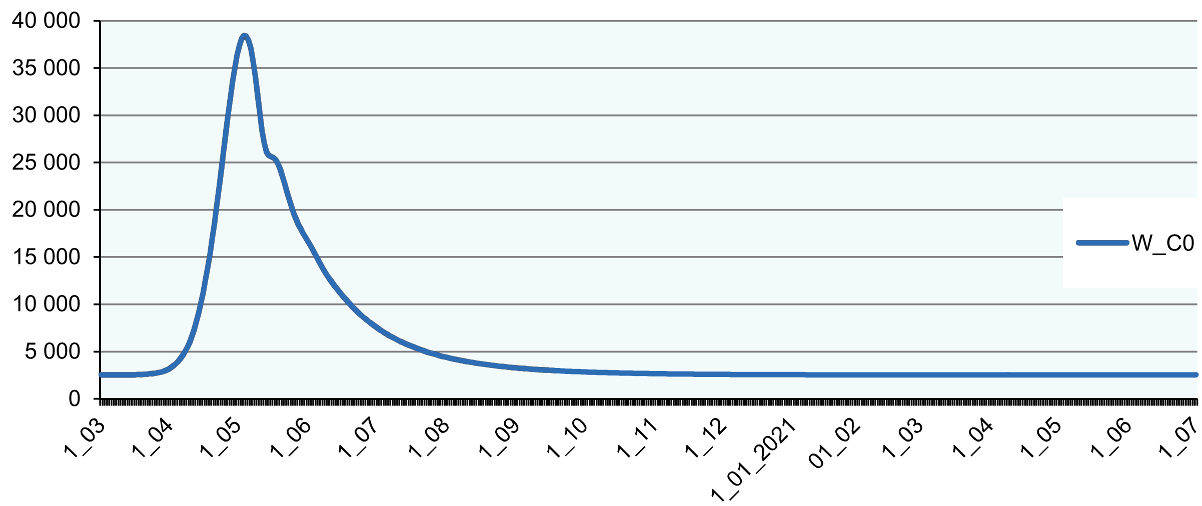

Fig. 6. Dynamics of the daily number of infected cases according to the C0 baseline scenario (W_C0).

nificant reduction in EPMs. Under such conditions and in absence of vaccination, there is a high probability of a new surge in cases and an incidence peak (380,000) reached by mid-August 2021 (Fig. 7, W_C1.0).

Scenario C2.0 illustrates the likelihood of increased incidence (with a peak of 65 thousand in mid-June 2021), when there is a moderate reduction in EPMs, from late September to January 2021, and no vaccination (Fig. 7, W_C2.0).

Scenario C3.0 illustrates the likelihood of increased incidence (with a peak of 360 thousand in early January 2021), when there is a significant reduction in EPMs, from late September to January 2021, and no vaccination (Fig. 7, W_C3.0).

Thus, computational simulations have shown that the incidence rates are likely to increase if EPMs are scaled down and the vaccination is not available. At the same time, the daily incidence peak rates depend on the extent of EPM reduction and do not depend on the time when the reduction starts. The next stage of our research focuses on the vaccination coverage and rate required to prevent a sharp increase in the incidence.

Potential scenarios with different vaccination coverage of the population

Scenario C1.1: The vaccination of the population starts September 25, 2020 and the achieved level of measures is maintained till the beginning of March 2021 when EPMs can be significantly reduced. If the vaccination coverage gradually increases to 2 million people by January 1, 2021 and, then to 4 million people by the beginning of April, reaching the level of 6.5 million by the end of August 2021, the exponential in-

Table 1. Forecast scenarios — options for a complex of anti-epidemic measures

Scenarios	Isolation of infected persons and interruption of the transmission mechanism (hygiene measures at all socially significant facilities, social distancing, wearing masks and gloves, strengthening of personal hygiene)	Vaccination volume and rate* (total volume reached on the date 01.01.21 — 01.04.21 — 21.10.21)
Scenario C0 «Basic» (Fig. 6)	A *slight* decrease in measures from June 12 to September 2020, followed by their maintenance at the achieved level	No vaccination
Scenario C1.0 (Fig. 7)	*Significant* reduction in measures from March 2021	No vaccination
Scenario C1.1 (Fig. 8)	*Significant* reduction in measures from March 2021	2M — 4M — 6.5M
Scenario C1.2 (Fig. 8)	*Significant* reduction in measures from March 2021	300k — 2M — 6.5M
Scenario C2.0 (Fig. 7)	*Moderate* reduction in measures from September 2020*	No vaccination
Scenario C2.1 (Fig. 9)	*Moderate* reduction in measures from September 2020*	2M — 4M — 6.35M
Scenario C2.2 (Fig. 9)	*Moderate* reduction in measures from September 2020*	300k — 2M — 4.3M
Scenario C3.0 (Fig. 7)	*Significant* reduction in measures from September 2020*	No vaccination
Scenario C3.1 (Fig. 10)	*Significant* reduction in measures from September 2020*	2M — 2.3M — 2.3M

Note. *The beginning of the change in measures coincides with the beginning of vaccination — 25.09.2020.

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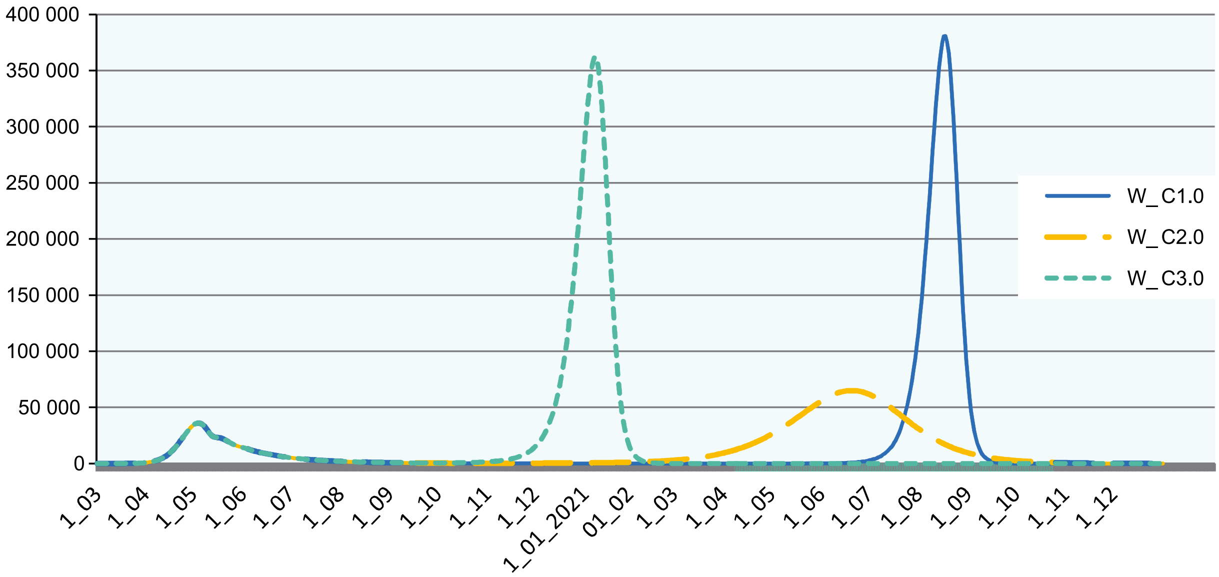

Fig. 7. The modeling of the daily incidence dynamics under scenarios C1.0, C2.0, and C3.0 without vaccination.

crease in the incidence observed with zero vaccination in scenario C1.0 (**Fig. 8**, W_C1.1) will be prevented.

Scenario C1.2L The isolation measures and the measures aimed at breaking chains of transmission are significantly reduced from March 2021 and the vaccination coverage (from September 25) is scaled down to 300 thousand people by January 1, 2021 and to 2 million people by early April 2021, totaling 6.5 million people vaccinated by mid-October 2021. It will not be possible to completely prevent the increase, and there will be a small second wave of Covid-19 with a peak (11,387 cases) in mid-December 2021. (Fig. 8, W_C1.2).

Thus, to prevent a significant increase in the incidence, the vaccination must be conducted together with the other EPMs (isolation and breaking chains of transmission) until the vaccination coverage reaches at least 2 million people. The measures (isolation and breaking chains of transmission) remaining in effect until a total vaccination coverage of 4 million people is achieved will it possible to prevent the so-called second wave. After 4 million people are vaccinated, EPMs can be reduced significantly. If the vaccination is administered until 50% of the Moscow residents are vaccinated, EPMs can be completely discontinued.

Scenario C2.1: A moderate reduction in EPMs from the end of September to January 2021, and the vaccination (from September 25) covering 2 million people by January 2021, 4 million people by March 2021 and 6.35 million people by October-November 2021 will result in a low incidence until January 2021, followed by a slight surge in cases with a peak (1,120 people) in mid-March (**Fig. 9**, W_C2.1).

Scenario C2.2: A moderate reduction in EPMs from late September 2020 to January 2021 and the

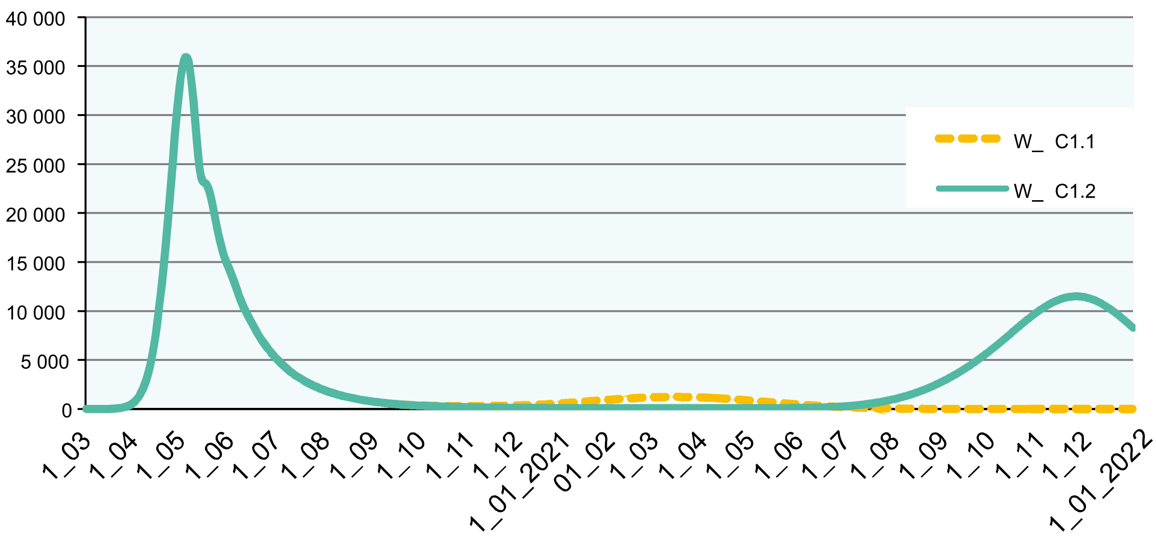

Fig. 8. Comparison between the daily incidence dynamics under the scenario of a significant reduction in measures (isolation and breaking chains of transmission) from March 2021 and different rates of vaccination.

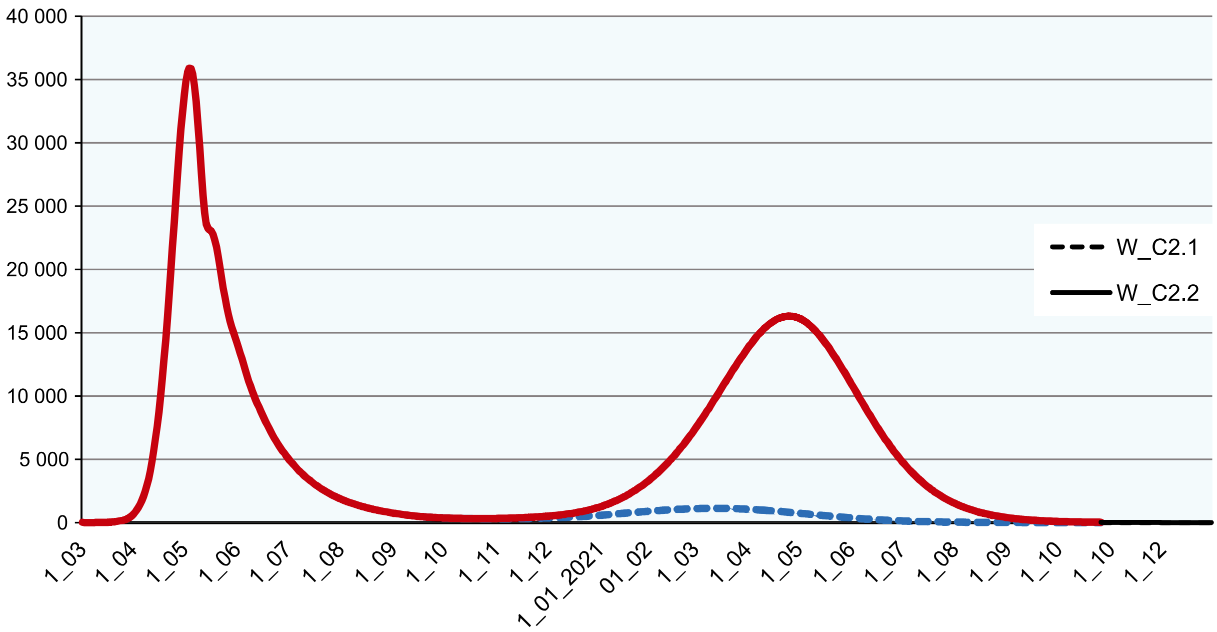

Fig. 9. Comparison between the daily incidence dynamics under the scenario of a moderate reduction in EPMs from the end of September to January 2021 and different rates of vaccination.

vaccination covering 300 thousand people by January 2021, 2 million people by early April and then 4.3 million by October 2021 will lead to a more significant increase in the daily incidence with a peak (18,302 people) at the end of April 2021. (**Fig. 9**, W_C2.2).

The vaccination conducted while EPMs (isolation and breaking the chains of transmission) are moderately reduced can contribute to the decreasing incidence, though its effectiveness depends on the time of its commencement, on its coverage and rate.

Scenario C3.1: A significant reduction in EPMs from the end of September to January 2021 will require a very high rate of vaccination within a short period by the 300th day (2021) before the incidence begins to rise. The coverage 2 million people reached by 2021 is not sufficient for preventing an exponential increase in the incidence with a peak of the second wave (220,000 people) reached by January 20, 2021. The above coverage helps decrease the incidence rate (from 360 thousand to 220 thousand people) (**Fig. 10**).

Thus, it has been shown that the vaccination accompanied by a significant reduction in EPMs will not prevent a significant increase in the incidence.

The summarized results of computational simulations under the potential scenarios are presented in **Table 2.**

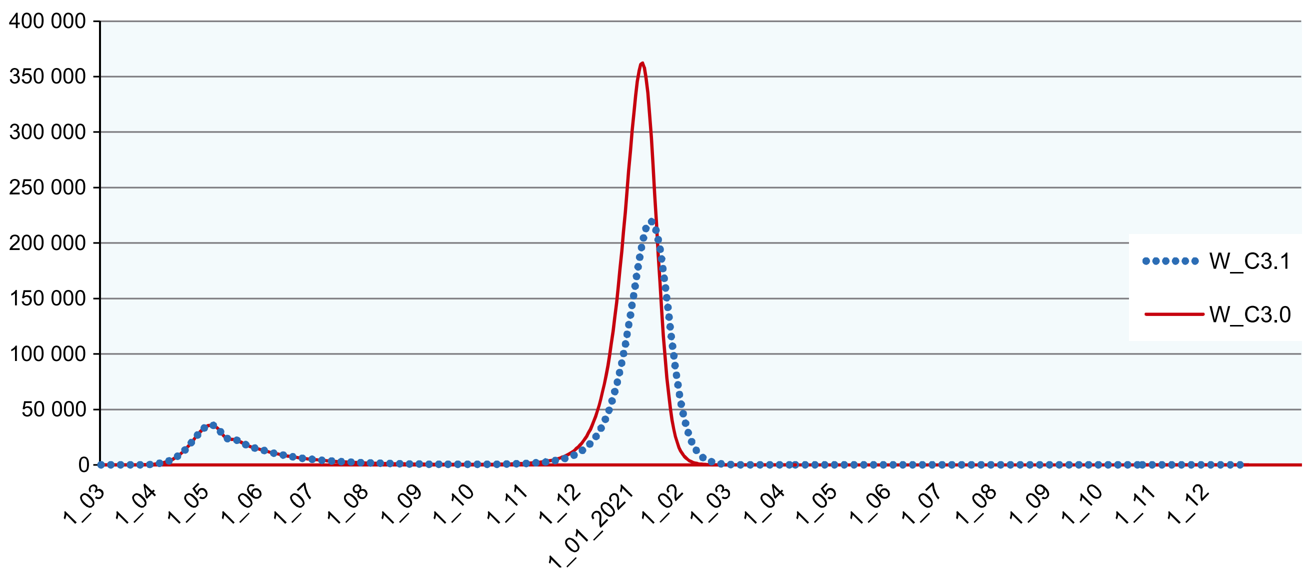

Fig. 10. Comparison between the daily incidence dynamics under the scenario of a significant reduction in EPMs from late September to January 2021 without vaccination (W_C3.0) and with vaccination (W_C3.1).

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Table 2. Simulation results for forecast scenarios

Scenarios	Vaccination	Dynamics of daily morbidity, peak	Cumulative number of infected (as of 01.02.2021)	Cumulative deaths (as of 01.02.2021)
Scenario C0 «Basic» (Fig. 6)	No vaccination	Daily morbidity — isolated cases after 01.01.2021	1 557 718	7789
Scenario C1.0 (Fig. 7)	No vaccination	The peak of the second wave of 380,000 people on day 530 (mid-August 2021)	10 737 123	53 686
Scenario C1.1 (Fig. 8)	Vaccinate	No rise in incidence	1 568 972	7832
Scenario C1.2 (Fig. 8)	Vaccinate	Rise in incidence with a peak of 11,317 people on day 662 (mid-December 2021)	2 691 315	13 082
Scenario C2.0 (Fig. 7)	No vaccination	The peak of the second wave of 65,000 people on day 430 (mid-June 2021)	7 678 221	38 391
Scenario C2.1 (Fig. 9)	Vaccinate	The increase in the incidence of 1120 people on day 378 (mid-March 2021)	1 717 293	8586
Scenario C2.2 (Fig. 9)	Vaccinate	Peak 18,302 cases on day 417 (end of April 2021)	3 610 443	18 052
Scenario C3.0 (Fig. 7)	No vaccination	Peak 360,000 cases on day 310 (20 January 2021)	10 728 363	53 642
Scenario C3.1 (Fig. 10)	Vaccinate	Peak 220,000 cases on day 320 (20 January 2021)	8 356 263	41 781

When comparing scenarios C0 and C1.0, the computational simulations illustrated a situation when the epidemic was already on the decline, but a significant reduction in EPMs (starting from March 2021) and the absence of vaccination can result in a high probability of a significant increase in the incidence (with a peak of 380,000 in mid-August 2021).

When comparing scenarios C1.0 and C1.1, the computational simulations showed that the vaccination (from the end of September) covering 4 million people before EPMs are significantly reduced prevents the occurrence of a second wave of the disease.

When comparing scenarios C1.0 and C1.2, the computational simulations showed that, while the incidence is low, the vaccination (from the end of September) starting from 300 thousand people, then reaching 2 million people and, finally, covering the total of 6.5 million people, does not completely prevent the increase in the daily incidence (with a peak of 11,317 cases in mid-December 2021).

When comparing scenarios C0 and C2.0, the computational simulations showed that the moderate reduction in EPMs in September 2020 and the absence of vaccination will result in low incidence rates until mid-November 2020 to be followed by an increase in the incidence with a peak (65,300) in mid-June 2021.

When comparing scenarios C2.0 and C2.1, the computational simulations showed that the moderate reduction in EPMs in September 2020, the vaccination (from the end of September 2020), the total coverage of 6.35 million people and the moderate rate of vaccination (2 mln — 4 mln — 6.35 mln) will help prevent the second wave of the disease (at the end of April 2021). There is a slight increase in the incidence (11,20 cases) in mid-March 2021.

When comparing scenarios C2.0 and C2.2, the computational simulations showed that the moderate reduction in EPMs, the vaccination (from the end of September 2020), the total coverage of 4.3 million people and the lower rate of vaccination (300 thousand — 2 million — 4.3 million) will help decrease the incidence. There is a slight increase in the incidence (18,302 cases) with a peak at the end of April 2021.

When comparing scenarios C0 and C3.0, the computational simulations showed that the significant reduction in EPMs in September 2020 and the absence of vaccination will result in a low incidence until November 1, 2020 to be followed by an exponential increase in the daily incidence (360,000 cases) with a peak in early January 2021.

When comparing scenarios C3_0 and C3_1, the computational simulations showed that the significant reduction in EPMs in September, the vaccination (from the end of September) at a moderate rate (2 million — 2.3 million — 2.3 million) and the maximum possible total coverage of 2.3 million people cannot prevent the occurrence of a second wave. The vaccination helps decrease the daily incidence rates from 360,000 to 220,000.

Implications

1. There is a high probability of an increase in the incidence if EPMs are reduced and the vaccination is absent. However, daily incidence rates depend on the extent of reduction in EPMs, hardly depending on the time when the reduction takes place.

2. The commencement of vaccination accompanied by a significant reduction in EPMs does not prevent a significant increase in the incidence;

3. The vaccination accompanied by a reduction in EPMs (isolation and breaking chains of transmission) can decrease the incidence, but the impact depends on the time of its commencement, its coverage and rate.

4. To prevent a significant increase in the Covid-19 incidence during the vaccination, the other EPMs (isolation of the infected and breaking chains of transmission) must be maintained until the vaccination coverage reaches approximately 2 million people. Ideally, EPMs should remain effective until the total vaccination coverage of 4 million people is reached' then, EPMs can be significantly reduced. When the vaccination coverage reaches 50% of the Moscow population, EPMs can be completely discontinued.

Conclusion

The modeling was not intended for making an accurate prediction of development of the epidemic situation in Moscow. Our research by using scenarios was aimed at finding opportunities for managing the epidemic situation in different versions of its development. The computational simulations show that the appropriate strategy in EPMs and vaccination will prevent the so-called second wave of Covid-19 epidemic. The optimum solution is to keep maintaining EPMs until a total vaccination coverage of 4 million people is reached, after which EPMs can be significantly reduced. When the vaccination coverage reaches 50% of the Moscow population, EPMs can be completely discontinued.

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