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Prospects for the use of artificial intelligence to predict the spread of tuberculosis infection in the WHO European Region

Objective — to analyze the prospects of using artificial intelligence and neural networks to create a geospatial model of TB transmission and forecast its spread in the WHO European Region using available analytical databases.

Materials and methods. The research was carried out for the period October 2022 — March 2023. Digital access to the following full-text and abstract databases was used as the main source of research: the EBSCO Information Base Package, the world's largest single abstract and scientific metric platform Scopus, the freely accessible search system Google Scholar, MEDLINE with Full Text, Dyna Med Plus, EBSCO eBooks Clinical Collection, the abstract and scientific metric database of scientific publications of the Thomson Reuters Web of Science Core Collection WoS, statistical data from the Ministry of Health of Ukraine and the Public Health Center, SCIE, SSCI, the online database of the National Scientific Medical Library of Ukraine, AHCI.

Results and discussion. Migration processes in Europe still remain a global trend and create difficulties for countries that receive migrants. Adverse living conditions, close contact, poor nutrition, mental and physical stress are what refugees and migrants face. The combination of these risk factors and insufficient access to health services increases the vulnerability of refugees to TB infection. In addition, a delay in diagnosis leads to poor treatment outcomes and continued transmission of the infection to other people.

The optimal way to predict the spread of TB infection in European cities, where a significant number of migrants from Ukraine arrived, is to create a mathematical model using the analytical technology of neural networks and artificial intelligence. By analyzing a large amount of data, artificial intelligence can quickly and efficiently identify connections between various factors and predict the future development of the epidemic. For example, artificial intelligence can analyze data on the incidence of TB in different regions of the world, as well as data on the number of patients with other diseases that can affect the human immune system, and make a forecast about the development of the epidemic in the future.

Conclusions. Today, the creation of a mathematical model and the development of a simulator program for the geospatial functioning of the city and the interaction of people during the day are relevant. Understanding the natural history of TB among recently arrived migrants is important as we consider how best to implement TB control in such populations.

Keywords

Epidemic, tuberculosis, neural networks, modeling.

Historically, human migration has had a major impact on the spread of tuberculosis (TB). Our country, as well as the European Union (EU) in general, is experiencing the largest migration crisis since the Second World War. An unprecedented number of forced migrants from Ukraine flooded European countries [1, 13].

War always increases the risks of the spread of various infectious diseases, tuberculosis is no exception. Population migration, overcrowding at checkpoints and accommodation, instability in the country, economic troubles, poverty are the factors that provoke the spread and growth of tuberculosis [6, 13].

The medical system of Ukraine adapted to the challenges of wartime and any patient with tuberculosis can seek help from the nearest anti-tuberculosis facility in the region where he was evacuated [1].

Currently, despite high rates of migration, the phenomenon of migration itself as a risk factor for the spread of tuberculosis is poorly studied. Mass migration automatically entails a decrease in the effectiveness of TB control measures in healthcare facilities and ensuring epidemiological safety for both sides: the countries receiving migrants and the countries of their origin, especially those with a high burden of active and drug-resistant tuberculosis [7, 16].

Taking into account the situation today with the large migration wave of citizens of Ukraine caused by the full-scale aggression of the Russian Federation, we are interested in the development and creation of a working model for predicting the spread of tuberculosis infection in the countries of the WHO European region that have received the largest number of refugees from Ukraine [10].

Modeling the spread of airborne bacterial infections is an urgent and unsolved task of modern science [11]. The availability of adequate and accurate models of stimulators is the basis for planning a strategy to prevent the spread of TB in countries with a low incidence rate.

Previously published results from cohort studies demonstrated a likely positive correlation between the number of new migrants to the EU and TB detection rates. It has also been established that a significant number of tuberculosis cases (up to 70 %) registered in Europe are among the population born outside of Europe [15, 24].

All of the above indicates the relevance of the research topic we have chosen, as an analytical model with adequate and reliable results would be of great benefit to practical healthcare, specifically in the development of plans to counter the spread of tuberculosis in the WHO European Region.

Objective — to analyze the prospects of using artificial intelligence and neural networks to create a geospatial model of tuberculosis transmission and forecast its spread in the WHO European Region using available analytical databases.

Materials and methods

The research was conducted from October 2022 to March 2023. Digital access to the following full-text and abstract databases was used as the main source of research: the EBSCO Information Base Package, the world's largest single abstract and scientific metric platform Scopus, the freely accessible search system Google Scholar, MEDLINE with Full Text, MEDLINE Complete, Dyna Med Plus, EBSCO eBooks Clinical Collection, the abstract and scientific metric database of scientific publications of the Thomson Reuters Web of Science Core Collection WoS (CC), statistical data from the Ministry of Health of Ukraine and the Public Health Center, SCIE (Science Citation Index Expanded), SSCI (Social Science Citation Index), the online database of the National Scientific Medical Library of Ukraine, AHCI (Art and Humanities Citation Index).

The search also included open access preprint repositories, as some scientific publications on similar models are only available there, which explains the absolute relevance of the topic.

The search was carried out using the search query of the following keywords: «geospatial models», «stochastic models», «modeling the spread of tuberculosis», «tuberculosis in Europe».

We use artificial neural networks for search and analysis. Artificial neural networks are one of the branches of machine learning that was started back in the 1940s. This approach is based on biological neural networks in mammals, which consist of neurons in the brain and spinal cord of the central nervous system. Of course, artificial neural networks are a much simplified interpretation of biological ones and only seek to solve problems that our brain solves every day. Neural-like networks have gone through a long way of formation and development, from the complete denial of the possibility of their application to the implementation in many spheres of human activity. According to the classic multi-agent SIR-model, a set of agents is generated that can move freely in a certain flat space that simulate a city. Each agent can have three conditions: S — healthy and susceptible to the disease, I —infected, which can infect others, R —recovered or not susceptible to the disease.

Results and discussion

Migration processes in Europe remain a global trend and create difficulties for countries that receive migrants [7]. In connection with the military actions in Ukraine, this process has acquired more extensive features of displacement of a significant number of Ukrainian citizens, in most cases, to the territories of the EU countries. It is natural that such a situation creates a number of problematic issues, in particular, in the field of providing medical services, which need to be resolved through political cooperation between countries [24].

Recently, data from a cohort study conducted in 28 European Union countries, as well as Iceland

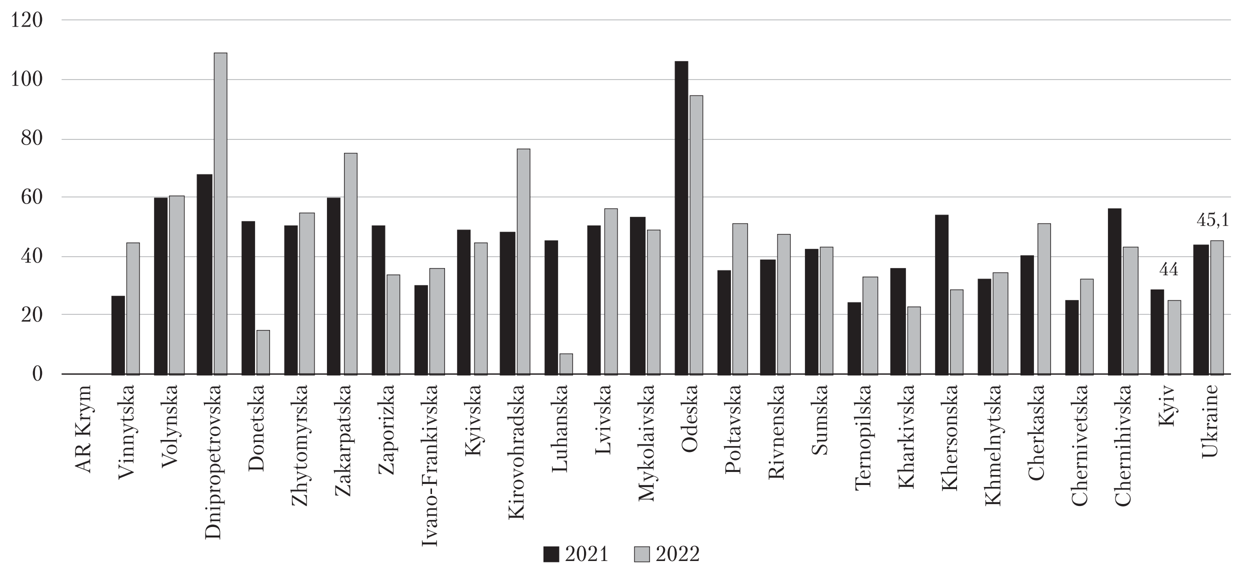

Fig. 1. **Incidence of tuberculosis in Ukraine (compared to 2021—2022) [5]**

and Norway, were published [26]. Pearson correlation analysis for each country and all countries taken together was analyzed for the period 2011—2017 to identify potential correlation between the annual number of immigrants and the incidence of tuberculosis per 100,000 population. The obtained and summarized results showed a significant negative correlation between the number of immigrants and the level of tuberculosis incidence in 22 out of 30 countries. However, in three countries (Germany, Italy, and Norway), a significant positive correlation was observed between the level of tuberculosis detection and the number of immigrants [9].

Adverse living conditions, close contact, poor nutrition, mental and physical stress are what refugees and migrants face [4]. The combination of these risk factors and insufficient access to health services increases the vulnerability of refugees to TB infection. In addition, a delay in diagnosis leads to poor treatment outcomes and continued transmission of the infection to other people [18].

In the geopolitical context, taking into account the high relevancy of the migration process and the risk of developing active tuberculosis, preventive examination of migrants should be performed by both parties: both the receiving party and the country of origin [6].

The World Health Organization (WHO) declares that improving the diagnosis and treatment of TB among migrants can be considered as a key health priority for the elimination of tuberculosis in general and the implementation of the «End TB» strategy [24].

As demonstrated by our retrospective analytical study, ongoing surveillance of TB migration and epidemic indicators is essential, as there is a need to harmonize case definitions and reporting standards to optimize TB control programs in Europe.

According to separate analytical sources, as of the end of 2022, almost 7.6 million Ukrainian citizens are officially abroad due to military operations in Ukraine [1].

Translation: By the end of 2022, Poland granted the largest number of temporary protection statuses with almost 1.5 million, followed by Germany with over 1 million and approximately 450,000 in the Czech Republic. More than 100,000 Ukrainians were also registered in Italy, Spain, Bulgaria, Great Britain and France [1, 13].

A significant problem faced by migrants, including those from Ukraine, is the lack of access to information about the spread, prevention and treatment of tuberculosis. Fear of stigma, lack of awareness of entitlement to health services, and low ability to spend on health care relative to income all contribute to reluctance to seek help or adhere to treatment. Economic deprivation and social marginalization can further exacerbate the spread of TB among migrants.

At the time of the beginning of the mass migration of Ukrainian citizens, the TB incidence rate in our country was 44 cases per 100,000 population (currently this rate is 45.1) (Fig. 1).

As forecasts show, the COVID-19 pandemic also has a negative impact on morbidity and mortality from tuberculosis in countries with a high incidence of tuberculosis (Fig. 2) [20, 23].

Long-term multifactorial epidemiological studies have shown that one patient with an active form of TB with bacteremia infects 10—15 contacts during the year [2, 19]. The risk of developing active tuberculosis in an infected person is 5—10 % throughout life.

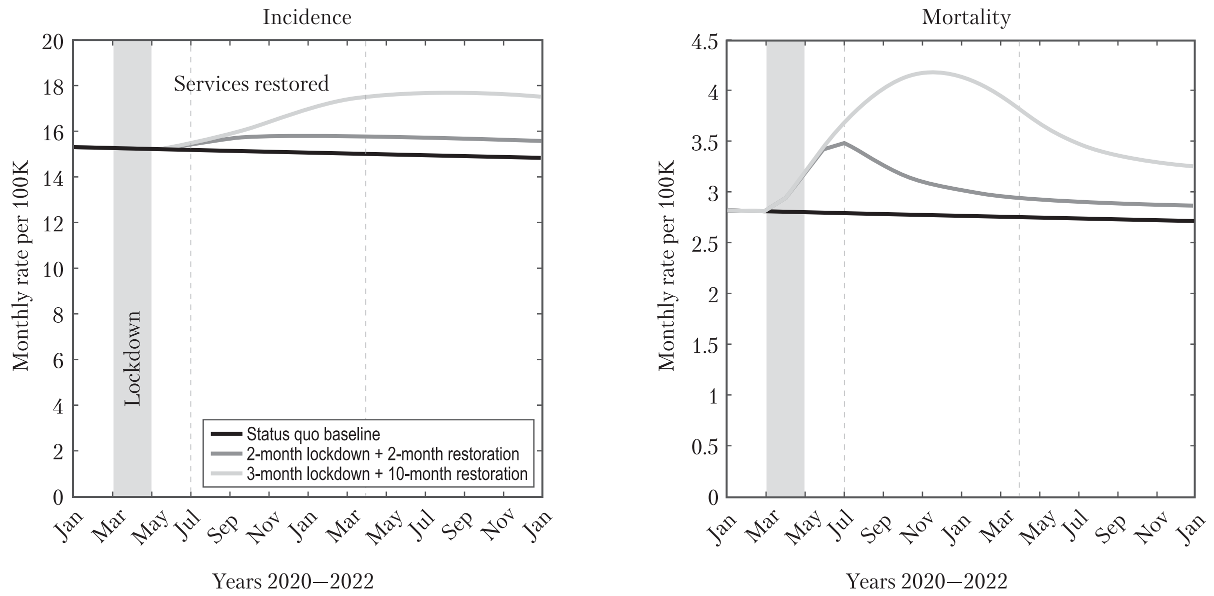

Fig. 2. **The potential impact of the COVID-19 response on tuberculosis in high-burden countries: a modelling analysis — StopTBpartnership [5]**

Thus, in our opinion, migrants who arrived from Ukraine, where the incidence of TB is higher than the epidemic threshold, may pose a threat to the fight against tuberculosis in EU host countries with a low incidence rate. Of course, among them there are also people who treat tuberculosis.

One of the challenges facing the medical community and the anti-tuberculosis service is ensuring access to therapy in the new location. After all, to overcome tuberculosis, the issue of regularity and continuity of taking drugs is fundamental.

According to the latest analytical data, more than 90 % of the adult population of Ukraine are infected with tuberculosis mycobacteria [25, 26]. Military actions on the territory of Ukraine, which have been going on for more than a year, have created unfavorable living conditions, close contact among internally displaced persons, mental and physical stress — what refugees from all countries face. The combination of these risk factors and insufficient access to medical services contributes to the transition of latent tuberculosis infection (LTI) to an active tuberculosis process.

Taking into account all of the above, the optimal way to predict the spread of TB infection in European cities, where a significant number of migrants from Ukraine arrived, is to use a mathematical model using the analytical technology of neural networks and artificial intelligence [21].

Prediction of epidemiological processes is an important task that helps to understand and predict future trends in the development of diseases and epidemics. Artificial intelligence can be a very useful tool in this task [21].

By analyzing large amounts of data, artificial intelligence can quickly and efficiently identify connections between different factors and predict the future development of an epidemic. For example, AI can analyze data on incidence in different regions of the world, as well as data on the number of people with other diseases that can affect the immune system, and make a forecast about the future of the epidemic [21].

Moreover, artificial intelligence can be used to model epidemiological processes and test different treatment and prevention strategies. For example, computer modeling can determine which prevention measures will be most effective in preventing the spread of tuberculosis in a particular region [12].

Therefore, artificial intelligence can be a very useful tool in forecasting epidemiological processes and performing various tasks in the field of health care. However, it is important to remember that artificial intelligence cannot replace the experience and expertise of people, so it must be used with understanding and caution.

The model of the spread of tuberculosis infection can be divided into 2 components: the model of the environment in which the infection spreads and the model of the spread of the infection itself. Our team is developing the first component, namely the construction of an adequate and accurate simulator model of life, behavior and interaction of people at the level of, for example, a city.

Classic SIR model. According to the classic multi-agent SIR-model, a set of agents is generated that can move freely in a certain flat space that simulate a city. Each agent can have three conditions: S — healthy and susceptible to the disease, I — infected, which can infect others, R — recovered or not susceptible to the disease [21]. The following data must be initialized for the modeling:

1. Area and shape of the territory (S).
2. Number of agents (N).
3. Average speed (v).
4. Initial positions of infected and uninfected agents (L = li=1, N(x, y)).
5. Distance necessary for the infection (d).
6. Probability of an infection if a healthy person comes close to an infected person (p).
7. Percentage of people who have immunity to the illness or have recovered (PR).
8. Duration of illness (Til).
9. Mortality rate (D).

One of the most important aspects of simulation is the comparison of computer time and linear dimensions with the corresponding real-world data. When simulating a real city, such quantities as S and N are given empirically. All other parameters are calculated by scaling the real geographical scale and statistics of the settlement.

After all, the spread of mycobacterium tuberculosis begins with the fact that an infected person living in the city contacts other people and spreads the infection. Combining such models in multiple cities will allow to simulate the spread of the epidemic at the level of the region, the state and the world as a whole. It is also clear that graphic maps, geospatial location of buildings and people should be used when modeling real objects of urbanization. This will make it possible, in addition to statistical data, to investigate the features of the geospatial spread of the pandemic [17].

1. In general, the following requirements can be identified that a mathematical model-simulator must meet for a reliable forecast.
2. It must be adequate and as plausible as possible.
3. It should be relatively easy to implement.
4. It should be able to take into account various factors, such as categories of people, age characteristics, different types of objects in which people live, work or spend their leisure time, etc.
5. It should take into account personal parameters of immunity and ways of transmission of infection.
6. It should simulate the life and contacts of people as realistically as possible, in particular:
   - take into account age and immune characteristics of people;
   - take into account the peculiarities of the daily schedule and location of the residents;
   - simulate people's contacts depending on the schedule and circle of communication (family).
7. It should display the results on a geographical map.
8. The model should be fast in calculation for the possibility of conducting a large number of computer experiments for learning a neural network with reinforcement, in order to choose the best strategy for preventing epidemics.
9. It should have the ability to parallelize, which will make it possible to use computer clusters to calculate and stimulate this model at the macro-level of states and the world [8].

As follows, TB control in high-income countries has historically focused on early detection and treatment of active TB with concomitant contact tracing. However, given the high number of TB cases among migrants, there is an ongoing debate about how best to identify TB among migrants. Therefore, the search for new technologies that allow predicting an epidemic situation in real time, with the impact of specific factors, using artificial intelligence technologies with its neural network base, will allow to control this process and prevent potential risks of increasing the spread of an infectious agent.

Therefore, the epidemiological and medico-economic analysis [24] carried out showed that the fight against TB in high-income countries would benefit from the use of targeted screening and treatment of LTBI in a certain category of migrants from countries with a high burden of tuberculosis. However, to fully control the situation, it will be necessary to solve the following problems: timely programming of the probable number of persons who are carriers and spreaders of tuberculosis infection, with the maximum coverage of their etiotropic treatment, and the complete completion of the program of anti-tuberculosis therapy. This is essential to ensure the effectiveness of the implementation of the «End TB» program. Prospects for the use of artificial intelligence to predict the spread of tuberculosis infection in the WHO European Region are undoubtedly a priority.

Conclusions

1. Taking into account the published statistical data on the migration wave of citizens from Ukraine during the war period (more than 7.6 million people to the countries of the European Union), we can apply a forecasting algorithm neural networks to predict the epidemiology of the main indicators of tuberculosis infection. This is important because a significant increase in the number of infected persons among the population of the countries of the European region of the WHO will have negative economic consequences at the national goverment level.

2. Prevention and control of the spread of tuberculosis in society is based on timely tracking of close

contacts and rapid prophylactic treatment of LTI, as well as effective treatment of active tuberculosis disease. All countries with significant internal migration from countries with a high burden of tuberculosis should consider additional targeted active screening among recent migrants and take into account the medical, social and economic effects of this problem.

3. Based on the above, today it is relevant to create a mathematical model and develop a program based on it to simulate the geospatial functioning of the city and the interaction of people during the day. Understanding the natural history of tuberculosis among recently arrived migrants is important as we consider how best to implement TB control in such populations.

There is no conflict of interest.

Participation of the authors: research concept and design — L.D. Todoriko, Y.I. Vyklyuk, I.O. Semianiv; collection of material — I. Margineanu, E. Lesnik, D.V. Nevinsky, I.V. Yeremenchuk; material processing — O.A. Andriiets, L.D. Todoriko, I. Marginianu, E. Lesnik, I.O. Semyaniv; writing the text — Y.I. Vyklyuk, L.D. Todoriko, I.O. Semianiv, I. Margineanu; statistical processing of data — I. Margineanu, E. Lesnic; text editing — O.A. Andriiets, L.D. Todoriko, Y.I. Vyklyuk.

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Перспективи застосування штучного інтелекту для прогнозування поширення туберкульозної інфекції в Європейському регіоні ВООЗ

Мета роботи — проаналізувати перспективи застосування нейромереж для створення геопросторової моделі передачі туберкульозної інфекції і прогнозування її поширення в Європейському регіоні ВООЗ з використанням доступних аналітичних баз.

Матеріали та методи. Дослідження виконано у період з жовтня 2022 р. до березня 2023 р. Як основне джерело досліджень використано цифровий доступ до таких повнотекстових і реферативних баз даних: EBSCO Information Base Package, найбільша в світі єдина реферативна та науковометрична платформа Scopus, вільнодоступна пошукова система Google Scholar, MEDLINE з повним текстом, Dyna Med Plus, EBSCO eBooks Clinical Collection, реферативна і науково-метрична база даних наукових публікацій Thomson Reuters Web of Science Core Collection WoS, статистичні дані МОЗ України та Центру громадського здоров'я, SCIE, SSCI, онлайн-база даних Національної наукової медичної бібліотеки України, AHCI.

Результати та обговорення. Міграційні процеси в Європі є глобальною тенденцією і створюють складнощі для країн, які приймають мігрантів. Несприятливі умови життя, тісний контакт, погане харчування, психічний і фізичний стрес — те, з чим стикаються біженці та мігранти. Поєднання цих чинників ризику і недостатній доступ до медичних послуг підвищує вразливість біженців до туберкульозної інфекції. Крім того, затримка з діагностикою призводить до поганих результатів лікування та продовження передачі інфекції іншим особам.

Оптимальним шляхом прогнозування поширення інфекції туберкульозу (ТБ) у містах Європи, в які прибула значна кількість мігрантів з України, є створення математичної моделі із застосуванням аналітичної технології нейромереж та штучного інтелекту. За допомогою аналізу великої кількості даних штучний інтелект може швидко та ефективно виявляти зв'язки між різними чинниками та прогнозувати розвиток епідемії. Наприклад, штучний інтелект може аналізувати дані про захворюваність на ТБ у різних регіонах світу, а також дані про кількість хворих на інші захворювання, які можуть впливати на імунну систему людини, і спрогнозувати розвиток епідемії в майбутньому.

Висновки. Актуальним є створення математичної моделі та розробки на її основі програми-симулятора геопросторового функціонування міста і взаємодії людей протягом доби. Розуміння природного перебігу ТБ серед недавно прибулих мігрантів є важливим для визначення способів боротьби з ТБ у таких популяціях.

Ключові слова: епідемія, туберкульоз, нейромережі, моделювання.

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