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Teaching Mathematical Modeling in Epidemiology: Organizational Issues

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ABSTRACT

BACKGROUND: One of the current tasks of higher medical education in epidemiology is the teaching of mathematical and statistical modeling methods for the spread of mass diseases.

AIM: To investigate the existing systems of teaching mathematical modeling and forecasting, with an emphasis on agent-based simulation approaches, in medical universities compared to non-medical and technical universities in Russia.

METHODS: As part of this descriptive and evaluative study, the curricula for the teaching of mathematical modeling, implemented at universities at various educational levels, were explored. The study included the curricula of non-medical universities (n = 31) and medical education institutions (n = 16).

RESULTS: In medical universities, the teaching of mathematical modeling is organized at various levels, including specialist, undergraduate, graduate and postgraduate levels. The total workload of such curricula ranges from 18 to 324 hours. The following specific topics were mentioned in the thematic plans: mathematical epidemiology; the SIR model and its modifications; ordinary differential equations; machine learning and simulation modeling systems in medicine and healthcare; simulation modeling of medical and biological processes, and others. Based on the results of the study, significant differences in the organization of teaching mathematical modeling in non-medical universities were identified.

CONCLUSION: Various levels of education in medical universities include certain aspects of forecasting and modeling the spread of infections. There is a substantial potential for teaching relevant topics in residency and postgraduate programs. In medical universities, mathematical modeling in the field of preventive medicine and epidemiology serves as a tool to foster intellectual curiosity, promote the development of thinking, positively impact the professional orientation of future health system specialists, and contribute to the mathematical component of professional competence in medical education.

Keywords: mathematical modeling; forecasting; teaching; modeling; competence.

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Преподавание математического моделирования в курсе эпидемиологии: организационные вопросы

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АННОТАЦИЯ

Обоснование. Одной из современных задач высшего медицинского образования в сфере эпидемиологии является преподавание методов математического и статистического моделирования распространения массовых заболеваний.

Цель исследования — изучение сложившихся систем преподавания математического моделирования и прогнозирования с акцентом на имитационные агентные подходы в медицинских университетах в сравнении с немедицинскими и техническими вузами России.

Материалы и методы. В рамках описательно-оценочного исследования изучены рабочие программы соответствующих дисциплин для преподавания вопросов математического моделирования, которые реализуются в вузах на разных уровнях образования. В работу вошли рабочие программы немедицинских вузов (n=31) и образовательных учреждений медицинского профиля (n=16).

Результаты. В медицинских вузах преподавание математического моделирования организовано на разных уровнях подготовки: специалитет, бакалавриат, магистратура и аспирантура. Общая трудоёмкость рабочих программ составляет от 18 до 324 часов. Среди специфических вопросов, фигурировавших в тематических планах, отмечены следующие: математическая эпидемиология; SIR-модель и её модификации; обыкновенные дифференциальные уравнения; системы машинного обучения и имитационного моделирования в медицине и здравоохранении; имитационное моделирование медико-биологических процессов и др. По результатам исследования определены существенные отличия в организации преподавания математического моделирования в немедицинских университетах.

Заключение. На разных уровнях образования в медицинском вузе предусмотрен разбор некоторых аспектов прогнозирования и моделирования распространения инфекций. Имеется значительный потенциал преподавания соответствующих тем в ординатуре и аспирантуре. В медицинском вузе математические модели в области профилактической медицины и эпидемиологии выступают средством развития познавательного интереса, способствуют развитию мышления, положительно влияют на организацию профессиональной направленности будущих врачей, формируют математическую составляющую профессиональной компетентности образования.

Ключевые слова: математическое моделирование; прогнозирование; преподавание; моделирование; компетенция.

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BACKGROUND

Given the critical role of mathematical modeling—including scenario forecasting—in understanding the world and its processes, the teaching of its various aspects in higher education and the training of competitive professionals remain highly important priorities [1–9].

Modeling the behavior of biological systems is known to occupy a distinct and essential place in science [10, 11], and the development of robust mathematical models capable of accurately describing epidemic processes is of particular interest [10, 12, 13]. When clinical or field trials are not feasible, randomization is impossible, or essential resources are unavailable, modeling becomes the preferred method. Moreover, the analysis of infectious disease spread using modeling platforms provides researchers with a powerful tool for evaluating the effectiveness and safety of preventive and anti-epidemic interventions. Therefore, addressing approaches to mathematical and statistical modeling in medical universities—particularly to support epidemiology—and assessing the relevant competencies being developed is a pressing task for higher medical education at this stage [12, 14, 15].

The work aimed to examine existing systems of teaching mathematical modeling and forecasting, with a focus on simulation-based agent approaches in medical universities, and to compare them with programs offered at nonmedical and technical universities in Russia.

MATERIALS AND METHODS

Study Design

It was a cross-sectional observational sample-based study.

The objects of analysis were the syllabi of relevant disciplines implemented at various levels of higher education institutions.[1]

Eligibility Criteria

Inclusion criteria: Educational documents were identified using Google search and through the official websites of medical and nonmedical universities. Syllabi were selected through total sampling. There were no restrictions regarding the geographic location of the institution.

Exclusion criteria: Syllabi were excluded if they related to secondary vocational or veterinary education, lacked essential factual information, or were not relevant to mathematical modeling.

Study Description

The following data were collected for synthesis and analysis: name of the university or institution; title of the syllabus and year of approval; type of discipline (core, elective, etc.); level of education; field of study; number of hours allocated to lectures, laboratory work, and practical sessions; and the content of the curriculum.

Ethics Approval

Not applicable.

Statistical Analysis

Descriptive statistics for continuous variables are presented as mean ± standard deviation ($\bar{x} \pm \sigma$) or median [interquartile range, Me (Q1; Q3)], depending on data distribution. Categorical variables are presented as percentages. Semantic analysis of the texts was performed using the Russian software platform PolyAnalyst 6.5.26 Rev.21. Statistical analysis was carried out using the R programming environment, version 4.2.1 (RStudio).[2]

RESULTS

Participants

The analysis included 47 syllabi of relevant disciplines implemented in Russian medical and nonmedical (technical) universities at various levels of higher education.

For the comparative analysis of approaches to teaching mathematical modeling and forecasting, syllabi of relevant academic disciplines from medical universities in several Russian cities were examined. This was followed by an overview of how mathematical modeling instruction is organized in institutions of other specializations (e.g., technical universities).

Primary Results

Teaching in Medical Universities

Mathematical statistics and methods for analyzing morbidity data have traditionally been included, in one form or another, in the epidemiology curricula across all major faculties of medical universities. Today, the ability to model and forecast the spread of mass phenomena related to public health is of great importance for epidemiologists, biostatisticians, and data scientists.

The medical universities whose syllabi were included in the study were located in 15 cities across 8 federal districts. The institutions represented a broad range, including: state medical universities in Vladivostok, Voronezh, Yekaterinburg, Kemerovo, Kirov, Omsk, Pyatigorsk (branch), Rostov-on-Don, Ryazan, Tver, Ufa, and Chelyabinsk; research medical universities in Moscow (Federal State Autonomous Educational Institution of Higher Education, Russian National Research Medical University named after N. I. Pirogov, Ministry of Health of the Russian Federation), Nizhny Novgorod, and

[1] Federal State Educational Standards [Internet]. fgos.ru. Available at: https://fgos.ru/ Accessed on December 16, 2024.

[2] R Core Team (2021). [Internet]. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/ Accessed on December 16, 2024.

Saint-Petersburg (Federal State Budgetary Institution Almazov National Medical Research Centre, Ministry of Health of the Russian Federation);and a multidisciplinary university in Moscow—Federal State Autonomous Educational Institution of Higher Education, Patrice Lumumba Peoples' Friendship University of Russia (RUDN University).

According to the documents reviewed, the teaching of mathematical modeling is organized at various levels of education: specialist degree programs, as well as bachelor's, master's, and postgraduate programs. Topics related to mathematical modeling are incorporated into general statistics courses and, as a rule, are included in the mandatory (core) part of the syllabus. Notably, in the vast majority of cases (69%), courses covering modeling and forecasting were delivered at the specialist level. Typically, students in specialist programs were introduced to this section of statistics in their first or second year and, less frequently, in the fourth year.

Relevant topics were in demand across 9 fields of study: biology, clinical psychology, general medicine, preventive medicine, medical biochemistry, public health, pathological anatomy, dentistry, and pharmacy. The syllabi from medical universities included in the analysis were approved between 2018 and 2024, most frequently in 2020 (4 documents), and in 2023–2024 (6 documents combined).

The titles of 15 syllabi from medical universities that included a modeling component were reviewed:

- Biostatistics
- Biostatistics and Mathematical Modeling
- Introduction to Biostatistics and Mathematical Modeling
- Informatics, Medical Informatics
- Informatics, Medical Informatics and Statistics
- Informatics, Medical Informatics, Medical Statistics
- Mathematics
- Mathematical Models in Biology and Medicine
- Mathematical Analysis
- Mathematical Modeling in Biology
- Medical and Biological Statistics and Mathematical Modeling
- Fundamentals of Biostatistics
- Practical Statistics and Mathematical Modeling
- Statistical Methods in Evidence-Based Medicine
- Statistical Methods and Mathematical Modeling in Psychology

The term modeling was found in the titles of 8 documents. The most frequently used lexical unit was biostatistics, which was generally expected.

The total workload specified in the syllabi ranged widely, from 18 to 324 hours, with a median of 108 hours (Q1; Q3: 72; 137.5).

The types of academic activities specified in the syllabi included lectures (mean, 20.07 ± 8.62 hours), practical classes (46.2 ± 38.72 hours), laboratory work (36 and 4 hours; in only 2 syllabi), and independent student work (51.18 ± 35.09 hours). Virtually all types of activities—except for laboratory work—were commonly included in the structure of syllabi at medical universities. One syllabus included all 4 types of student activities.

The number of sections (or topics) in the syllabi ranged from 2 to 14. Standard biostatistics topics typical of higher medical education were present, including statistical hypothesis testing, correlation and regression analyses, time series analysis, and others. At the same time, the syllabi also included important topics directly related to modeling:

- mathematical epidemiology, Holling's predator-prey model, and the SIR epidemic spread model
- ordinary differential equations
- multilayer neural networks
- artificial intelligence systems and simulation modeling in medicine and public health (e.g., development of a simulation model of a hospital emergency department or an ophthalmology department)
- simulation modeling of biomedical processes
- development of a simulation model for epidemic spread, among others

It should be taken into account that in medical universities, biostatistics is traditionally taught by several departments (e.g., physics, epidemiology, public health). As a result, aspects of forecasting and modeling may be addressed in a fragmented manner as students progress through different departments, highlighting the need for a unified educational trajectory.

The experience of several institutions in conducting educational activities related to the application of mathematical modeling for epidemiological purposes is particularly noteworthy. In particular, an author-developed scientific and practical lecture and seminar series titled "Expanded Set of Modern Mathematical Methods in Epidemiological Practice" (36 academic hours, July 2023) was implemented by the Federal Budgetary Institution of Science Central Research Institute of Epidemiology of the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Central Research Institute of Epidemiology of Rospotrebnadzor).[3]

At the Federal State Budgetary Educational Institution of Higher Education Privolzhsky Research Medical University of the Ministry of Health of Russia (PRMU), a web-based application titled Medical Atlas[4] was developed and integrated into the educational process. This digital educational tool

[3] Federal Budgetary Institute of Science Central Research Institute of Epidemiology, Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Rospotrebnadzor) [Internet]. Author's scientific and practical educational course of lectures and seminars "*An Extended Set of Modern Mathematical Methods in Epidemiological Practice*", dated August 3, 2023. Available at: https://www.crie.ru/about/news/novosti-instituta/avtorskiy-nauchno-prakticheskiy-obrazovatelnyy-tsikl-lektsiy-i-seminarov-rasshirennyy-nabor-sovremen/ Accessed on December 16, 2024.

[4] Privolzhsky Research Medical University [Internet]. Priority 2030A. Medical Atlas. Available at: https://pimunn.ru/development/meditsinskiy-atlas/ Accessed on December 16, 2024.

includes, among other components, an "epidemic map" module. This module can be used not only to visualize the spread of infections in urban environments, but also to teach the principles of compartmental modeling (using the SIR and SEIR models as examples).

The experience of colleagues in Ufa is also noteworthy. The activities of the Laboratory of Mathematical Modeling at the Institute of Fundamental Medicine, Federal State Budgetary Educational Institution of Higher Education Bashkir State Medical University of the Ministry of Health of Russia, are focused on the development of mathematical and computational models for various biomedical applications.[5]

Another example is the educational program "School of Mathematical Modeling in Pharmacy," conducted by the Federal State Autonomous Educational Institution of Higher Education Sechenov First Moscow State Medical University of the Ministry of Health of Russia (Center for Mathematical Modeling in Drug Development) in collaboration with the Federal State Budgetary Scientific Institution (FSBSI) Marchuk Institute of Numerical Mathematics of the Russian Academy of Sciences (5 days, March 2024). The program focused on population pharmacokinetic models and systems pharmacology models, addressing the specific needs of the pharmaceutical field.[6]

Thus, modern medical education provides opportunities for teaching various aspects of the development and application of mathematical models in the study of infectious disease epidemiology. At the same time, several features of modeling education in medical universities should be highlighted: the specific nature of medical education; training within the paradigm of evidence-based medicine; differences in the etiology of diseases as the subject of epidemiological study; the natural science–oriented mindset of medical students; a generally lower level of proficiency in higher mathematics and mathematical analysis compared with students of technical universities; and the need to develop digital competencies, among other factors.

Teaching in Nonmedical Universities

When forming the sample, relevant course syllabi were obtained from 26 nonmedical universities representing 7 of the 8 federal districts of the Russian Federation. The universities included in our sample, located in 21 cities across Russia, were conditionally grouped into two categories: classical universities (e.g., Federal State Budgetary Educational Institution of Higher Education (FSBEI HE) Lomonosov Moscow State University, Federal State Autonomous Educational Institution of Higher Education (FSAEI HE) Siberian Federal University, FSBEI HE Chelyabinsk State University, FSBEI HE Kuban State University, among others; a total of 12 institutions) and technical universities (e.g., FSBEI HE Saint Petersburg State University of Civil Aviation named after Chief Marshal of Aviation A.A. Novikov, FSBEI HE Nizhny Novgorod State Technical University named after R.E. Alekseev, FSBEI HE Perm National Research Polytechnic University, FSBEI HE Voronezh State Technical University, among others; a total of 14 institutions).

The teaching of mathematical modeling in nonmedical universities is organized at various levels of education:

- 13 bachelor's courses (core curriculum: 5; elective curriculum: 8, including 1 optional course);
- 9 master's courses (core curriculum: 5; elective curriculum: 4, including 1 optional course); and
- 7 postgraduate courses (core curriculum: 4; elective curriculum: 2; optional course: 1).

The syllabi for courses in modeling highlight the diversity of training programs—19 fields in total. Unsurprisingly, the majority of programs that incorporate mathematical modeling are related primarily to mathematics and applied mathematics, computer science, information technology, computing, and computational sciences. Equally noteworthy are programs in which mathematical modeling is also included, such as public and municipal administration, landscape architecture, youth work management, teacher education, construction, radio engineering, ecology, and environmental management (see Table 1). Thus, the need to teach the theory and practice of mathematical models extends to a number of other important disciplines, including those in the humanities.

As a result of the search, syllabi approved between 2015 and 2024 came into focus, with the largest share of documents dated 2022 and 2023 (together accounting for 48% of all selected programs). A semantic analysis of the document titles proved both interesting and informative, offering a clearer understanding of the directions in which modeling is taught in nonmedical universities. This linguistic and stylistic examination revealed three groups of syllabi with similar titles: Mathematical Modeling (6 items); Mathematical Modeling, Numerical Methods, and Software Packages (5 items); Mathematical Modeling in Economics and Management (2 items); and Mathematical Modeling of Information Systems and Processes (2 items). Program titles often contained direct references to the field of activity targeted by the instruction, namely: economics and management, biology, urban ecosystems, construction, and engineering. The syllabi reflected a focus on both general issues of mathematical modeling and the specific characteristics of information, environmental, economic, social, socioeconomic and technological, biological, and chemical-technological processes.

The total workload specified in the syllabi included in this analysis ranged from 70 to 396 hours, with a median (Me) of 108 hours (Q1; Q3: 99; 144) (see Fig. 1).

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[5] Bashkir State Medical University [Internet]. Priority 2030A. Laboratory of Mathematical Modeling. Available at: https://bashgmu.ru/science_and_innovation/megagranty/grant-nots-rmg-2021/laboratorii/81287/ Accessed on December 16, 2024.

[6] Sechenov First Moscow State Medical University (Sechenov University [Internet]. School of Mathematical Modeling in Pharmacy [March 25–29, 2024]. Available at: https://www.sechenov.ru/search/?q=Школа+математического+моделирования+в+фармацевтике&s=Поиск Accessed on December 16, 2024.

Table 1. Fields of study where mathematical modeling is in demand

Field of study	Course syllabi
Mathematics and computational technology	☒
Mathematics and computer science	☒
Mathematics and mechanics	☒
Applied mathematics	☒
Mathematical modeling, numerical methods, and software packages	☒ ☒
Fundamental informatics and information technologies	☒
Computer science and computing technology	☒ ☒ ☒
Applied informatics	☒ ☒ ☒
Applied mathematics and informatics	☒ ☒ ☒ ☒ ☒
Landscape architecture	☒
Construction engineering and technologies	☒
Civil engineering	☒ ☒ ☒
Radio engineering	☒
Energy- and resource-saving processes in chemical technology, petrochemistry, and biotechnology	☒
Electric power engineering and electrical engineering	☒ ☒
Public and municipal administration	☒
Ecology and environmental management	☒
Youth work management	☒
Pedagogical education	☒

Note. ☒ indicates one course syllabus.

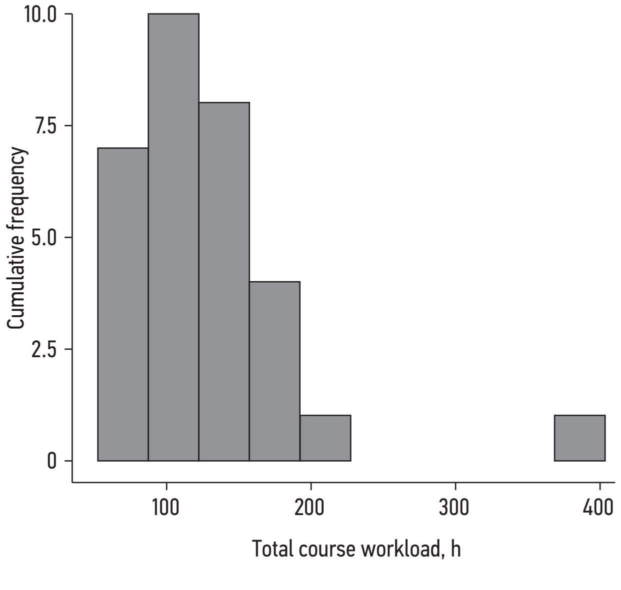

Fig. 1. Description of the workload of the courses as specified in the syllabi.

The types of academic activities listed in the syllabi included lectures (mean, 23.77 ± 3.36 hours), practical classes (26.31 ± 3.53 hours), laboratory work (26.31 ± 3.53 hours), and independent student work (71.71 ± 6.77 hours). The most frequently represented activity was independent work, found in 30 syllabi from nonmedical universities (almost 100% of the reviewed documents). Lectures were the second most common, included in 26 syllabi. Practical classes were present in 52% of the reviewed syllabi, and laboratory work involving personal computers was included in 35%.

It is noteworthy that all four types of academic activities were included in only 3 syllabi (FSBEI HE Admiral Makarov State University of Maritime and Inland Shipping; FSBEI HE Moscow Technical University of Communications and Informatics; FSAEI HE Russian University of Transport), while three types were found in 12 syllabi (39%). In such cases, lectures and independent work were supplemented by either practical classes or laboratory sessions.

The structure of the syllabi varied in terms of the number of thematic sections, ranging from 1 to 20, with a mean of 6 sections (topics). The core content typically included the following topics: the nature of modeling; basic concepts; model properties; classification approaches; general principles and objectives of modeling; stages of model development; model adequacy; and evaluation of modeling results. In addition to general issues, many syllabi (39% of those analyzed) also covered topics directly related to simulation modeling. Notably, the simulation approach was addressed in nearly all the reviewed documents. It is worth noting the diversity of topics related to simulation modeling presented in the relevant sections of the syllabi:

- simulation modeling methods, their characteristics, algorithms, typical tasks, and planning of simulation experiments
- advantages and disadvantages of the simulation approach
- agent-based modeling
- the Monte Carlo method and modeling of discrete Markov random processes
- computer and simulation modeling systems
- programming languages used for simulation modeling
- simulation modeling as a tool for integrating models of various classes
- simulation modeling in managerial decision-making and the search for optimal solutions

Particular attention should be given to the inclusion of components related to the biomedical field in some syllabi. Notable examples include a differential model of diabetes mellitus (FSBEI HE Chelyabinsk State University); mathematical models in biology (FSBSI Blagonravov Institute of Mechanical Engineering, Russian Academy of Sciences; FSBSI Federal Research Center “Kazan Scientific Center,” Russian Academy of Sciences); and predator–prey models and SIR epidemic models (FSAEI HE Kazan (Volga Region) Federal University).

DISCUSSION

There is no doubt that mathematical modeling is a universal method of scientific inquiry involving the construction of a model that represents the object under study. The existing studies describes the key concepts of mathematical modeling, its general principles, advantages, and limitations. Several classifications of mathematical models have been proposed, the stages of their development have been described, as well as possible applications in medical science [11]. The organization of teaching model construction and validation in technical and classical universities certainly differs from the approaches used in medical educational institutions. This fact may be taken into account when developing and optimizing course syllabi in medical schools, particularly in the field of epidemiology.

The present study does not claim to be exhaustive due to its selective nature and the impossibility of covering all currently implemented syllabi. At the same time, the chosen design provided valuable insights into the current system of teaching mathematical modeling of various processes, including biological ones, at universities with different academic profiles.

In the current context, the content of medical education in the area of mathematical modeling and epidemiology should include the following instructional aspects: content aligned with course objectives; enhanced motivation to study modeling-related disciplines; and the development of instructional tools and methodologies for their implementation.

CONCLUSION

The importance of mathematical models in medical education is currently extremely high, particularly in the fields of preventive medicine and epidemiology. In particular, mathematical modeling serves as a tool for fostering cognitive interest, supports the development of analytical thinking, positively influences the formation of professional orientation among future physicians, and contributes to the development of the mathematical component of professional competence in education.

ADDITIONAL INFORMATION

Author's contribution. N.V. Saperkin: data collection and analysis, writing and editing the manuscript. The author provided approval of the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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