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The value of mathematical modelling approaches in epidemiology for public health decision making

La utilidad de los modelos matemáticos en epidemiología para la toma de decisiones en salud pública

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Abstract

It is discussed the relevance of quantitative approaches, specifically mathematical modelling in epidemiology, in the public health decision-making process. This topic is discussed here based on the experience of various experts in mathematical epidemiology and public health. First, the definition of mathematical modelling is presented, especially in the context of epidemiology. Second, the different uses and socio-political implications, including empirical examples of recent experiences that have taken place at the international level are addressed. Finally, some general considerations regarding the challenges encountered in the use and application of mathematical modelling in epidemiology in the decision-making process at the local and national levels.

Key words

Mathematical modelling; Epidemiology; Public health; Decision making; Anesthesiology.

Resumen

Se trata sobre la importancia de los abordajes cuantitativos, específicamente la formulación de modelos matemáticos en epidemiología, dentro del proceso de toma de decisiones en salud pública. Esta importante temática se analiza basándose en la experiencia de algunos expertos en epidemiología matemática y salud pública. En primer lugar, se presenta la definición de modelación matemática, particularmente dentro del contexto de la epidemiología. En segundo lugar, se abordan los diferentes usos y las implicaciones socio-políticas, incluyendo ejemplos de experiencias recientes que han ocurrido a nivel internacional. Finalmente, se hace referencia a ciertas consideraciones generales respecto a los retos que representa el uso y la aplicación de modelos matemáticos en epidemiología para el proceso de toma de decisiones a nivel local y nacional.

Palabras clave

Modelamiento matemático; Epidemiología; Salud pública; Toma de decisiones; Anestesiología.

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INTRODUCTION

Mathematical modelling, understood as the use and application of quantitative methods to study the behavior and distribution of different health events -including infectious diseases- and the associated health processes, allows for a reliable representation of the biological processes observed in nature. (1) In the area of public health and epidemiology, mathematical modelling adds value to conventional analysis by providing strategic information for the design of mechanisms for the protection, care and promotion of health in society. (1,2) In scenarios with high uncertainty and in a highly interconnected world, the risk of disease transmission between continents, countries and/or regions and cities within the same country is a factor of the utmost importance. Moreover, limited budgets for managing public health crisis represent additional pressure on policy makers and decision makers, who are expected to optimally allocate accessible health resources (e.g., laboratory tests, vaccines, etc.) to reduce the burden of local or national disease and mortality (3), particularly when dealing with public health emergencies when, in addition to the lack of information, there is little time for decision making.

These remarks are intended to contribute to assess the usefulness of mathematical modelling in the context of public health policy makers and decision makers. Specifically, as a problem-solving tool in complex situations where quality of life and subsequent demographic processes, such as birth or death rates or aging, may be significantly affected. (4) Furthermore, mathematical modelling could play a key role in epidemiology by providing an effective framework for the search for evidence-based solutions in emergency situations, including the management of future pandemics.

Mathematical epidemiology, a tool or a trend?

The implicit mission of mathematical modelling in epidemiology is to capture and replicate - as closely as possible – real life scenarios through the use of different designs and the construction, application and analysis of a process or system. This approach facilitates the incorporation of uncertainty and the complex interaction of factors, as well as the potential impact of solutions and decisions in natural processes. This exercise facilitates and improves decision-making processes, which are strongly based on and shaped by concrete conclusions and direct interpretation of evidence. (5) The advantage of the mathematical approach lies in its precise language, with well-defined rules and the fast and reliable performance of complex numerical calculations that use extensive computational resources to produce results. (6) An advantage that can also be applied and used to inform the general public and target populations not only about problems, but also about the potential impact of a given range of solutions and thus to inform future decisions.

A first step in the construction of mathematical models - and in general in any research project - is the design of a relevant research question and the conceptual definition of the problem of interest. This represents the key objective, where the qualitative integration of existing information and a description of the system to be modelled can be performed, and is subject to changes as circumstances evolve. (4,7) This process is complemented with the illustration of the theories supporting the problem, which subsequently translates into the description, evaluation and quantitative validation of the process. This step is defined as the mathematical formalization process, which comprises optimization, parameter calculation, critical evaluation of suitability, simulation and prediction, among others activities. Finally, the results of mathematical models in epidemiology can be compared with the real situation, which also generates feedback to iteratively make adjustments to the assumptions and parameters of the model based on the current realities. (1,4,8)

Mathematical modelling in epidemiology, a new concept?

According to Brauer and Castillo-Chavez (9), there is apparently some positive association between the maturity of a scientific field and the frequency with which it develops, applies and analyzes mathematical models to understand its systems, according to real-world evidence.

Mathematical modelling in epidemiology originated with the work of Daniel Bernoulli during the second half of the 18th century, when he analyzed the benefits of inoculation against smallpox from an actuarial approach. Since then, increasingly complex models have been developed that include multiple factors and specific interrelationships that take place in biological systems. Among the most significant models there are those that involve the age of infection, vector-borne diseases, HIV/AIDS transmission models, heterogeneity of mixing -which takes into account super-spreaders-, the statistical-spatial approach, cross-immunity and co-infection, and drug resistance, among other relevant factors. (1,2,4)

These quantitative models, as a tool for planning and designing emerging and persistent infectious disease control programs, allow explicit assumptions to be made, test different types of hypotheses, identify patterns of epidemic spread, account for cost parameters (e.g., cost-effectiveness, cost-benefit, cost-utility, etc.), quantify potential adverse outcomes, and estimate the possible impact of some measures. Over time, policy makers and decision makers in public health have increasingly considered the contribution of mathematical modelling. These are mainly used as a theoretical-practical tool in the analysis of communicable diseases, to address the problems of prevention, diagnosis, treatment and control of the spread.

One of the transcendental aspects that may impact the use of mathematical modelling as a tool is clear and timely communication. Two-way communication between the modelling team and policy makers is essential; this involves a clear and pedagogical communication of all aspects related to the purpose, scope, model selection, assumptions, development, use and interpretation of the mathematical systems. In other words, everything related to the completeness and handling of the models. In this regard, the guidelines of the international actuarial standard of practice on model governance (10) are a valuable reference, which provides clear and systematic principles for greater transparency and assertiveness in the different stages of the knowledge transfer process, when communicating the results of mathematical modelling exercises.

Contemporary approaches of the mathematical epidemiology: consolidation for action?

The 21st century has witnessed the emergence of an increasing number of scenarios in which mathematical modelers have become highly relevant in advising on the management of epidemics and pandemics. A well-known example is what happened in the United States after the outbreak of influenza A (H1N1) pdm09, when the World Health Organization (WHO) convened an informal network of mathematical modelers and public health experts with the aim of assessing the dynamics of the virus and the effectiveness of different interventions. (11) Also, in 2016, WHO organized an event involving different universities from around the world to address how best to incorporate the results of mathematical modelling into its guidelines as a specialized international agency, highlighting that modelling "(...) may be more acceptable and more influential in situations where immediate action is called for, but little empirical evidence is available, and arguably more acceptable in public health than in clinical decision making". (12)

In the recent COVID-19 pandemic, multiple international institutions have developed different mathematical models. Different approaches have been used to analyze, for example, the magnitude of the spread of SARS-Cov-2 and what the infection rate would be in the presence of different non-pharmaceutical interventions implemented by the government (e.g., isolation of suspected cases and lockdown), and assess their effectiveness. Other initiatives have assessed the management of the demand for healthcare resources, optimization of restricted supplies of vaccines and drugs for critically ill patients (e.g., Intensive Care Units), shortages of clinical human resources, and the socioeconomic impact of confinements, among other topics of interest.

However, COVID-19 added new challenges to modelling. Given the evolving nature of the evidence on the multiple factors needed for modelling (e.g., incubation period, limitations in test sensitivity and specificity, limitations in access and timeliness of delivery of PCR test results, and the large percentage of asymptomatic cases), scientists had to deal with incomplete and often inaccurate data.

This situation demanded innovation and led to the use of potentially more up-to-date data, although not always accurate, such as bed occupancy levels, people's mobility, search engine queries, streams from social media such as Twitter and Facebook, among others, which allowed for higher quality and earlier forecasts. (13)

In this area, the technical studies carried out by the Imperial College COVID-19 Response Team (England), the University of Washington and the Centers for Disease Control and Prevention (United States) stand out. However, it is also important to recognize that, in addition to these initiatives in high-income countries, there was also an emerging use of these technologies among low- and middle-income countries (LMICs). To a greater extent, LMICs began to use mathematical modelling as a theoretical-practical research resource mostly for educational endeavors. However, its use as a tool was observed in universities, research centers, health technology agencies or national health institutes, working independently or as part of collaborative teams to contribute to the understanding of various scenarios, decisions and solutions during the pandemic.

Mathematical epidemiology during the pandemic, a new generation?

The urgency of the recent situation during the pandemic and the growing needs for solutions gave rise to an increased interest in science in general, and in epidemiology in particular. Thus, there is a wide scientific development with a broad dissemination of the available information and an important training of human capital in mathematical modelling. Other factors have also contributed during the pandemic: the digital interconnectivity of research networks, the data revolution and open sources, greater computational processing capacity, as well as the partial improvement of epidemiological information and surveillance systems. However, although all of these aspects are useful, they have been challenged by the complexity of the scenarios, the budgetary restrictions on investment in science, technology and innovation, the uncertainty of political scenarios, and the avalanche of misinformation, inter alia.

The attention and dissemination in the media (e.g., television and social media) of the use of mathematical modelling for decision-making in public health has also increased the common interest and acceptance of mathematical modelling as a key input for the formulation of public policies. Similar to other situations such as voting or electoral campaigns, the information disseminated through the media has an effect on the general population and the responsible leaders; depending on the political context and technocratic level they may realize the potential reach of the information on the mass of voters and may or may not consider the use of this information to make decisions on future actions in their process. (14) However, not all contributions or results of mathematical modelling exercises are heard, understood or applied by decision makers, timely or at all. Some experiences from the United States and Brazil show that, even with robust technical research teams, some control measures adopted in 2020 for the COVID-19 pandemic were not always consistent with the epidemiological recommendations. (15,16) In these examples, global and regional coordination at the political level was minimal and failed to contribute to controlling the epidemic at the time, which challenged the generation and utilization of epidemiological resources for decision making. (16)

On the other hand, a relative success story may be seen in Colombia, where since the middle of March 2020, under the leadership of the Instituto Nacional de Salud, a group called 'Modelling COVID-19 Colombia' was organized, with the participation of various people with managerial roles from technical entities of the health and government sector (e.g. Instituto de Evaluación Tecnológica en Salud, Departamento Administrativo Nacional de Estadística, Departamento Nacional de Planeación, in addition to some national and international universities, among other institutions). This technical-scientific group designed mathematical epidemiological models that provided information to the Minister of Health and Social Protection for real-time decision making. (17) In addition, a cost-benefit analysis was conducted to identify the optimal portfolio of vaccines against COVID-19 to be purchased by the country (18) and a cost-effectiveness analysis of the National Vaccination Plan against COVID-19, which provided a holistic view of risk management for the prioritization of immunization. (19) On the other hand, in an unprecedented action to join efforts in the history of the health sector in the country, it was possible to combine several databases to design a vulnerability interactive geographic viewer against COVID-19 (at the block level), in record time, and with a very robust technological infrastructure, Big Data techniques and high level data science. (20) This computational tool supported, among other things, informed decision-making for the allocation of cash transfers to the most vulnerable and pandemic-affected population, using real-world evidence.

The training, perceptions, attitudes, values and beliefs of decision-makers at local and national high levels of government are determinants for the adequate adoption and implementation of measures based on the results of mathematical modelling. There are additional limitations due to the inability to apply certain rules or assumptions in the specific local context or because of regional jurisprudence. To ensure that the work between decision-makers and modelers takes the most appropriate course and yields the maximum benefit, these efforts shall always be based on a relationship of mutual trust - hopefully long-term rather than temporary - to start from an adaptive language (e.g., graphical representations under clear, concise and high-impact statistical visualization principles), a relevant translation of knowledge including formal reporting (translated into cost-effectiveness / cost-benefit / cost-utility) and an adequate evaluation of the quality of the evidence of the analytical models developed. (3,15,21,22)

CONCLUSIONS

In summary, some of the challenges that mathematical modelling should continue to address for decision-making in public health are: i) continuous improvement in assertive and effective communication towards decision makers and the general population, with a view to a significantly better understanding among the various parties (i.e., strengthening trustworthy relationships between scientific and political teams); ii) significant funding for the development of cohort studies, systematic syndromic surveillance studies, and serological surveys that are able to determine, under the local context of each country (with its explicit regional diversity), the true status of the disease studied; iii) an interdisciplinary approach with a quantitative framework that finally translates into possible solutions; understanding not only the biological component, but also the complex social factors present in most territories worldwide, through an increasingly comprehensive perspective; and iv) in scenarios where the modelling incorporates clinical data as well as real-world evidence, there is a need to take underreporting into account and to understand the complexity of this information, knowing its history and meaning to the collectors of these data (field epidemiologists, clinical experts, among others).

New pandemics and challenges to the health and well-being of the population are likely to emerge in the future. Climate change, environmental problems, non-communicable diseases in aging populations with inadequate lifestyles, and the emergence and re-emergence of infectious diseases whose worldwide spread is favored by globalization, are imminent and substantial threats that require critical decisions and policies that should be based on the best evidence and science. In this regard, mathematical modelling could be instrumental in outlining scenarios and providing solutions, as well as in providing a framework for using and translating the growing development of data in the health domain. Effective solutions to global needs require data-driven and evidence-based approaches.

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Author's contributions

All authors contributed equally to the conception, drafting and revision of the article.

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