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Purple Paper

The Role of Mathematical Modelling in Public Health Planning and Decision Making

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Introduction

In simple terms, mathematical modelling is a scientific approach to formulating an explanation for an observed phenomenon and then testing this formulation to project the outcome of various experiments under pertinent conditions. There is vast scientific literature that provides compelling evidence for the role of mathematical and simulation models in public health and disease epidemics, in particular for evaluating the potential impact of intervention strategies and informing policy decision-making. Mathematical models are invaluable tools for planning; because by making assumptions explicit, mathematical models can test different hypotheses, and quantify anticipated risks, costs and benefits associated with disease control activities. This paper attempts to lay out a basic description of mathematical modelling and discusses its relevance to public health policy formulation. It also provides examples for the application of modelling to optimizing health policy and practice in the face of an emerging disease. The paper concludes by highlighting the importance of synergistic efforts for making such models more amenable to the needs of public health and policy makers for future planning.

Key Points

- Mathematical modelling has become a viable approach to evaluate the impact of public health intervention strategies and suggest the optimal course of action in the ongoing fight against persistent and emerging infectious diseases.
- Mathematical modelling provides an invaluable tool for making assumptions explicit, highlighting key factors determining policy needs, and providing quantitative predictions for the effectiveness and cost-effectiveness of disease control policies.
- There is much greater need than ever for effective communication between modellers, planners, and policy-makers to make modelling more amenable and applicable to the needs of public health planning and decision making.
- Knowledge translation activities remain a key component of modelling endeavours for guiding public health in times of crisis and informing decision-makers for policy effectiveness and the potential outcomes of different scenarios.

Modelling Contribution and Limitations

Mathematical modelling of human diseases has a long history, dating back at least a century (1900-1935) to the establishment of the foundations for epidemiological models of disease transmission by public health physicians, including Ross [1], Hamer [2], McKendrick and Kermack [3-5]. After a series of novel papers in theoretical epidemiology, in the 1930s Kermack and McKendrick established an extremely important principle, stating that the level of susceptibility in the population must be sufficiently high in order for an epidemic to unfold in that population. This principle was derived from a simple model describing the transmission dynamics of disease between susceptible, infected and recovered individuals in a homogeneously mixed population, the so-called classical SIR epidemic model [4,5].

Over time, mathematical modelling has proven to be a useful tool for identifying the patterns of disease spread during epidemics by projecting plausible scenarios using the best available information and data [6]. An important role for mathematical modelling and simulations that is being increasingly recognized relates to their ability to forecast optimal intervention strategies for limiting the impact of disease in the population under prescribed assumptions.

Historically, infectious disease outbreaks have demonstrated the need for planning and epidemic/pandemic preparedness to ensure that health resources are optimally allocated and utilized for reducing illness, minimizing death and preventing societal disruption within the target populations. Mathematical and simulation models of disease transmission have provided useful frameworks for planning [6]. In specific terms, such models can help describe the epidemiological status of the population, estimate transmissibility of the infectious agent and the potential impact of public health responses (e.g. vaccinations, drug therapy, community-based measures, infection control and hygiene practices), highlight risk factors, and identify more nuanced, targeted or geographically specific control strategies.

Model estimates of disease-specific parameters can help determine the prevalence of infection in a population, and therefore identify the type and intensity of target measures for mitigating disease spread.

Mathematical models can also characterize the nature of an emerging disease. Major characteristics that have been frequently explored by mathematical models include the latent period (i.e. the interval following exposure before an individual becomes infectious and transmits the disease), infectious period (i.e. the period during which an infected person can transmit a pathogen to a susceptible host) and transmissibility. Transmissibility is commonly referred to as the reproduction number, which is defined as the number of secondary cases generated by a single infected case introduced into an entirely susceptible population [7-11]. Model estimates of these disease-specific parameters can help determine the prevalence of infection in the population [12], and therefore identify the type and intensity of target measures for mitigating disease spread. Furthermore, mathematical models can address real-time challenges of emerging diseases such as maintenance of surge capacity in the hospital settings and long-term care facilities with regard to the required number of beds and intensive care units, pharmaceutical and non-pharmaceutical measures, and staff shortages [13]. Such information is crucial to policy-makers tasked with making difficult decisions for immediate implementation of public health responses in the face of an emerging crisis.

Despite its significant potential to contribute to the public health domain, mathematical modelling has limitations which are largely due to underlying assumptions of the model, and input data and information that may be incomplete or inaccurate. In addition, some limitations are inherent to the structure of the model itself, which involves a balance between predictive power of the model and its level of complexity, and depends on the type of questions to be addressed [14]. Decisions must therefore be made about which variables or parameters to include or exclude from the model, based on their relative importance and impact on the accuracy of predictions. Inclusion of more specific details (e.g. population structure and mobility patterns of the individuals, demographic variables, risk factors and age profiles) can increase the precision of formulating an epidemic scenario, but this also complicates the model and makes the projections subject to greater uncertainties. Nevertheless, mathematical models can encapsulate assumptions explicitly, highlight key factors determining policy needs, and provide quantitative predictions that can be considered when making health decisions [15].

Model-Based Policy and Planning

The 2003 severe acute respiratory syndrome (SARS) outbreak was the first major infectious disease epidemic of the 21st century, and it highlighted the importance of “planning” to meet the threat of emerging infections in the modern era of public health [16]. Although SARS outbreaks were relatively quickly contained, the disease resulted in substantial political and economic impact in affected countries. In the wake of the SARS experience, global public health research was stimulated to plan for an emerging influenza pandemic, especially in light of the sporadic human transmission of avian influenza A/H5N1 since 1997.

In planning for pandemic influenza, mathematical modelling and simulations have played a major role in evaluating response strategies in many countries, including the US, the UK, Canada and Australia. Early mathematical models, stochastic in nature dealing with many possibilities, attempted to inform plausible intervention strategies for containment of the disease at the source by simulating various scenarios for the onset of a pandemic in Southeast Asia [17,18]. However, growing concerns of public health personnel at the international level about being able to fulfill the requirements for pandemic containment as recommended by these models has led to further research on targeted strategies in different population settings [15]. Despite such exhaustive modelling activities, pandemic preparedness plans were based on many assumptions leading to great uncertainty about the origin, timing and nature of the pandemic.

The principal objective of Pan-InfORM was to develop innovative knowledge translation methodologies and inform policy-makers through modelling frameworks that forge strong links between theory, policy and practice.

The emergence of the H1N1 pandemic strain in North America in the spring of 2009 demonstrated how little we understand about the mechanisms by which influenza viruses arise and behave [19]. Although nations were prompted to activate their pandemic plans, inadequate information and data about the characteristics of this novel strain posed significant challenges for policy-makers to adapt preparedness measures for addressing the urgent needs of public health and make difficult decisions in the face of substantial uncertainty. In Canada, these challenges were overcome to some degree through extensive collaborative efforts and communication channels that were established following the SARS epidemic between modellers, public health planners and providers, and policy-makers [20]. An example of these interdisciplinary initiatives was the formation of the "Pandemic Influenza Outbreak Research Modelling" (Pan-InfORM) team during the early stages of the H1N1 pandemic [21]. The principal objective of Pan-InfORM was to develop innovative knowledge translation methodologies and inform policy-makers through modelling frameworks that forge strong links between theory, policy and practice. With its strong networking capacity, the team became a national entity with diverse expertise to apply mathematical models to create new knowledge and translate the outcomes for improving health policy, suggesting more effective clinical and public health services, and informing the Canadian health care system in response to the 2009 pandemic and future emerging infectious diseases.

Examples of policy questions that have been addressed by Pan-InfORM through mathematical modelling include optimal antiviral strategies for reducing illness while preventing the population-wide emergence of drug-resistance [22,23], optimal pandemic vaccine allocation for the Canadian population [24], and the synergistic effects of pharmaceutical interventions and social distancing mechanisms (e.g. school closure) [25]. Models employed here were developed and validated based on the best available information and data at the time. Such models may require further evaluation when taking into account information, data and evidence that have become available during and after the second wave of the H1N1 pandemic.

In addition to mathematical modelling efforts for policy effectiveness, the Pan-InfORM network conducted critical research to characterize the epidemiology of the H1N1 infection by using laboratory-confirmed case counts from the province of Ontario in a modelling framework [9]. This research provided estimates for the ranges of several key parameters pertaining to the nature of the disease, including the latent period, duration of illness and transmissibility. Furthermore, the work provided important information, such as the risk of hospital admission and case-fatality rates (i.e. the ratio of mortality to the cumulative incidence of infection over a specific period of time) associated with different age groups, which helped practitioners and health care providers better manage disease outcomes. These policy relevant findings were all based on a simple mathematical model that simulated, using stochastic methods, the observed patterns of H1N1 spread over a short duration following the onset of pandemic outbreaks. While delivering tangible messages to the public health planners and practitioners, the study highlighted the importance of timely access to the outcomes of surveillance activities that could be integrated with modelling endeavours for devising sound health policy and implementing effective intervention programs.

Although in Canada the H1N1 pandemic was perceived to be relatively mild for most individuals, it disproportionately affected some vulnerable populations (e.g. First Nations, Inuit and Métis peoples, and isolated and remote communities). New challenges of community health protection were encountered that must be addressed for future planning, harkening back to the need to ensure the inclusion of accurate information and realities of population health in the evaluation of modelling scenarios through involvement of those populations most affected by the disease. In a public health workshop evaluating Canada's response to the 2009 pandemic, participants highlighted these challenges and raised specific questions with regard to the effectiveness and cost-effectiveness of disease control policies [26]. Addressing these questions requires the development of carefully calibrated modelling frameworks to aid decision-making for the design of system-wide contingency plans that allow for more rational and efficient utilization of health resources in response to emerging diseases.

Synergistic Modelling and Planning

A common approach to public health planning has been the use of best available information and data, based on evidence and past experiences with outbreaks of a disease with similar characteristics. In making such preparedness plans more flexible and adaptable to addressing new challenges encountered during the spread of a novel disease, mathematical modelling can play a major role by illustrating different scenarios and their potential outcomes, allowing variability in health responses and epidemic profiles.

Modellers must involve knowledge translation activities to demonstrate the applicability of their results in the context of public health.

Mathematical modelling is an invaluable tool to support strategic public health decision-making regarding long-term plans using prescribed assumptions. However, the most important and difficult policy decisions are often operational and are concerned with the acute management of public health crises [20]. In the event of an emerging disease, there are several key questions that policy-makers need to address in order to make informed health policy decisions. First and foremost is whether the disease can cause a community outbreak, and if so, how quickly will the infectious pathogen spread through the population. Addressing this question requires that we understand the transmissibility of the disease. Mathematical models can provide this information, as was demonstrated during the early stages of the H1N1 pandemic [7-11]; but this requires access to reliable information and databases that represent the true picture of disease prevalence in the population. This highlights the need for establishing collaborative efforts and partnership between the modelling community, public health departments, and policy decision makers.

Estimating the transmissibility of disease alone through modelling frameworks will not be sufficient to inform or support challenging policy decisions. At this stage, modellers must involve knowledge translation activities to demonstrate the applicability of their results in the context of public health. For instance, estimates of transmissibility can be used to evaluate the effectiveness of intervention strategies, project surge capacity and determine the fraction of the population that must be vaccinated to halt the spread of infection. This practical information can be useful when effective communication is established and mathematical models are developed cooperatively by modellers and policy-makers to include plausible assumptions [15]. Such coordinated efforts between scientific, administrative and public health communities are crucial to providing the evidence-based information and applying practical knowledge to design and implement key intervention strategies by health professionals and practitioners.

Given the historical evidence and recent experiences with the 2003 SARS epidemic and 2009 H1N1 pandemic, it is natural to expect that mathematical models of disease epidemics will be more widely used by public health and medical personnel when implemented as user-friendly desktop decision-support tools. Canadian modellers have made significant attempts in this direction to understand the process of decision making and its underlying principles. They have helped to identify and overcome model limitations and to determine effective ways of communicating with policy-makers to inform planning strategies. These synergistic efforts must be continued and enhanced to ensure that the Canadian modelling capacity is maintained to address urgent needs of public health policy-makers. We hope that this short essay will set the stage for further expository discussions on the principles of mathematical modelling and its potential for guiding public health in times of crisis.

NCCID Comments

Mathematical modelling is a powerful tool for program planning and decision making in public health. The authors have discussed ways in which mathematical modelling was used during large-scale infectious disease outbreaks to describe the epidemiological parameters of the epidemics and to assess the timing and effectiveness of various public health mitigation measures, as in the case of the 2009 influenza pandemic. However, mathematical modelling can also be applied to the programming of day-to-day operations in public health. For example, mathematical modelling can examine the effectiveness and cost-effectiveness of different partner notification methods in the prevention and control of STBBIs. As such, modelling can help public health authorities decide how limited resources can be most wisely and effectively used based on the incidence and prevalence of STBBIs in their local context. Before mathematical modelling can be widely adopted, communication channels between public health practitioners and modellers must first be established. Together, they can investigate how mathematical modelling can address current programming uncertainties. By providing the modellers with local data, a context-appropriate model can be constructed to answer specific questions that practitioners have regarding their practice. This collaborative endeavour between academia and practitioners is another avenue toward evidence-based public health practice that should be further explored.

References

[1] Ross R. The Prevention of Malaria. 2nd edn, London, England: John Murray, 1911.

[2] Hamer WH. Epidemic disease in England, Lancet 1906; 1: 733–739.

[3] McKendrick AG. Applications of mathematics to medical problems, Proc Edin Math Soc 1926; 14: 98–130.

[4] Kermak WO, McKendrick AG. A contribution to the mathematical theory of epidemics, Proc R Soc Lond B 1927; 115: 700–721.

[5] Kermak WO, McKendrick AG. Contributions to the mathematical theory of epidemics, Proc R Soc Lond B 1931; 138: 55–83.

[6] Moghadas SM. Gaining insights into human viral diseases through mathematics, Europ J Epidemiol 2006, 21:337–342.

[7] Fraser C, *et al*. Pandemic potential of a strain of influenza A (H1N1): early findings, *Science* 2009; 324: 1557-1561.

[8] Pourbohloul B. Initial human transmission dynamics of the pandemic (H1N1) 2009 virus in North America, *Influenza Other Respiratory Viruses* 2009, 3:215-222.

[9] Tuite AR, *et al*. Estimated epidemiologic parameters and morbidity associated with pandemic H1N1 influenza, *CMAJ* 2010; 182: 131-136.

[10] White LF, *et al*. Estimation of the reproductive number and the serial interval in early phase of the 2009 influenza A/H1N1 pandemic in the USA, *Influenza and Other Respiratory Viruses* 2009; 3: 267-276.

[11] Yang Y, *et al*. The transmissibility and control of pandemic influenza A (H1N1) virus, *Science* 2009; 326: 729-733.

[12] Reed C, *et al*. Estimates of the prevalence of pandemic (H1N1) 2009, United States, April–July 2009, *Emerg Infect Dis* 2009; DOI: 10.3201/eid1512.091413.

[13] Smetanin P, *et al*. Potential intensive care unit ventilator demand/capacity mismatch due to novel swine-origin H1N1 in Canada. Can J Infect Dis Med Microbiol 2009; 20, 115-123.

[14] Nishiura H, *et al*. Pros and cons of estimating the reproduction number from early epidemic growth rate of influenza A (H1N1) 2009, *Theoretical Biology and Medical Modelling* 2010; 7: 1.

[15] Moghadas S, *et al*. Managing public health crises: the role of models in pandemic preparedness. *Influenza Other Respir Viruses* 2009; 3:75-9.

[16] Gumel, AB, *et al.* Modeling strategies for controlling SARS outbreaks. Proc Roy Soc B 2004; 271: 2223–2232.

[17] Ferguson NM, *et al.* Strategies for containing an emerging influenza pandemic in Southeast Asia. *Nature* 2005, 437: 209-214.

[18] Longini IM Jr, *et al.* Containing pandemic influenza at the source. *Science* 2005, 309: 1083-1087.

[19] World now at the start of 2009 influenza pandemic [press release]. Geneva (Switz erland): World Health Organization; 2009 June 11. Available: www.who.int/media_centre /news/statements/2009/h1n1_pandemic_phase6_ 20090611/en/index.html (accessed 2009 June 22).

[20] Moghadas SM, et al. Modelling an influenza pandemic: A guide for the perplexed. CMAJ 2009; 181: 171-173.

[21] Pan-InfORM Pandemic Influenza Outbreak Research Modelling Team (2009), http://pan-inform.uwinnipeg.ca

[22] Moghadas SM, *et al*. Post-exposure prophylaxis during pandemic outbreaks, BMC Medicine 2009; 7: 73.

[23] Hansen E, *et al*. Strategies for the use of oseltamivir and zanamivir during pandemic outbreaks. Can J Infect Dis Med Microbiol 2010; 21: e28-e63.

[24] Tuite A, *et* al. Optimal pandemic influenza vaccine allocation strategies for the Canadian population, PLoS Current Influenza 2010.

[25] Gojovic MZ, *et al*. Modelling mitigation strategies for pandemic (H1N1) 2009. CMAJ 2009; 181: 673-680.

[26] Moghadas SM, *et al*. Canada in the face of the 2009 H1N1 pandemic. Influenza Other Respiratory Viruses, in press (2010).

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