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ENDOGENOUS HUMAN BEHAVIOR IN MODELS OF COVID-19 TRANSMISSION: A SYSTEMATIC SCOPING REVIEW

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ABSTRACT

While mathematical models of disease have been important drivers of public policy since the eighteenth century, the incorporation of endogenous behavior driven by risk perception is a relatively recent phenomenon (Klein et al., 2007). Including behavior endogenously can enhance the utility of a model by providing a mechanism for how behavior varies in response to both control measures as well as the epidemic dynamics. We conducted a systematic scoping review to understand the extent to which endogenous behavior was incorporated into models of COVID-19 transmission.

1 INTRODUCTION

During the COVID-19 pandemic, results from dynamical forecasts were mixed, with models producing both under- and overestimates (Weitz et al., 2020). A major challenge was the behavior of individuals, which was guided by personal risk perception (Hanna et al., 2023). Incorporation of endogenous behavior in disease models prior to COVID-19 has largely been restricted to models of HIV and vaccination choices (Funk et al., 2010). We conducted a systematic scoping review of the mathematical approaches for including behavior endogenously, focusing on studies that compared model output to real-world data. The goal of this review is to inform researchers and decision-makers on the importance of incorporating endogenous behavior in dynamic models and to provide examples in the context of COVID-19.

2 METHODS

A PubMed search was conducted using a comprehensive search strategy comprised of three concepts: 1) dynamic modeling, 2) COVID-19, and 3) human behavior. Search results were imported into the Covidence Platform (Covidence systematic review software), and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for scoping reviews were followed (Tricco et al., 2018). Seven reviewers conducted title and abstract screening as well as full-text screening using a customized screening tool. We included studies that modeled a COVID-19 outcome, such as cases or deaths. Studies needed to include dynamic mathematical models (e.g., compartmental, agent-based, network, system dynamics, or Markov chain), and we excluded statistical models and machine learning models. We only included models in which behavior was an endogenous variable (i.e., behavior changed as a function of another dynamic variable within the simulation). Studies that included human behavior simply an

exogenous longitudinal input variable (e.g., mobility data) and studies that modeled behavioral responses by adjusting parameters exogenously at fixed time points were excluded. We recorded data on model type, approach to endogenous behavior, model compartments, randomness, population scale and mixing, time-step and simulation length, modeled outcomes, parameterization, validation, and health equity considerations.

3 RESULTS

The PubMed search resulted in 6,344 articles, among which 2,559 duplicates were removed, leaving 3,785 for title and abstract screening. One hundred ninety-six studies were selected for full-text screening, and 103 studies met all inclusion criteria. Types of behavior included vaccination, isolation, social distancing, and others. Behavior change resulted in modifying model parameters, changing the disease state of individuals, or modifying the contact structure of the network (Funk et al., 2010). We categorized approaches for including behavior endogenously into three groups: 1) feedback control system, 2) game theory/utility theory, and 3) information/opinion spread. A *feedback control system* uses the prevalence of a disease outcome (e.g., daily new cases) to stimulate a change in behavior dynamically. Seventy-one percent of studies (N=66) used a feedback control approach, and the majority of these employed compartmental models. *Game theory* is a technique to model how people make decisions in response to each other or some external initiative (Von Neumann and Morgenstern, 1944). Twenty-five percent (N=23) of studies used game-theoretic frameworks to study human behavior. Nine percent (N=8) included a model of *information or opinion spread*, in which an individual's behavioral susceptibility to infection was affected by opinions or attitudes, such as anti-vaccine views, that they acquired from others in the population. Six percent (N=6) of studies used more than one approach.

4 DISCUSSION

This review is not exhaustive as we only searched one database; however, included studies provide several examples of how to incorporate endogenous behavior in models of COVID-19 transmission. Most studies lacked formal validation to assess the robustness of adding behavior endogenously; however, studies that did demonstrated that its incorporation replicated multi-modal peaks as observed with real-world data. Despite the fact that models of the 2009 H1N1 pandemic showed that including behavior more effectively captured transmission, this was largely excluded in COVID-19 models used by the CDC to inform predictions. Investing in building better capacity for models with endogenous behavior now could potentially mitigate the burden of future pandemics.

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