Network epidemiology in the time of COVID-19

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Abstract. Network epidemiology integrates the characteristics of human behavioral and interaction patterns that serve as the backbone for the spread of pathogens with mathematical models of disease transmission. The pandemic of COVID-19 is a test of the current maturity of the field as a tool for advising public health decisions.

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The COVID-19 pandemic has often been compared to a war scene. With this warlike simile, the public has been aware of the efforts and sacrifices that had to be carried out during the difficult periods of confinement, in which we have witnessed how the disease took the lives of thousands of people, often alone and without the care of loved ones. Faced with such a state of health emergency, the first line of combat is occupied by physicians, nurses and other health personnel, who are the first force to contain the virus. The line of action is made up of scientists who, from different fronts, are facing the creation of tools with which to detect, cure and mitigate the devastating effects of COVID-19. From researchers who study the virus on a small scale and model its behavior to those who have the difficult task of developing vaccines or treatments to decrease the transmissibility of the virus, all the pieces of this great collaboration are necessary to stop the spread of SARS-CoV-2.

In this gear of scientific development there is a fundamental piece, epidemic forecast models, whose most recent development has gone hand in hand with non-linear dynamics, complex systems and data sciences. Unlike a conventional war, we lack spies who bring us information on the strategy to be followed. However, the advance of epidemic modeling during the last two decades provides us with a very powerful weapon, being the most advanced intelligence service to project the early spread of a pathogen and to evaluate what containment strategies are more appropriate given its characteristics.

Epidemic models, like meteorological ones, have their origins in modest equations that, however, managed to capture the essence of the phenomena studied. Two physicians, Ronald Ross and Anderson G. McKendrick (both closely related to India), and a chemist, William O. Kermack, laid the foundation for epidemiological modeling around the same time that physicist Lewis Fry Richardson proposed the first models for weather forecasting. In particular, McKendrik and Kermack, among other contributions, formulated in 1927 the celebrated SIR (susceptible–infectious–recovered) model [1, 2], which today remains a cornerstone of most of the current epidemiological models, and, following the studies carried out by Ross [3] to analyze the spread of malaria, introduced for their analysis the concept of reproductive number basic, \(R_0\). The usefulness of this number, however, went unnoticed until 1979, when Anderson and May applied it to study strategies for the control of infectious diseases [4].

Despite sharing the same time window in its beginnings, the evolutions of epidemic and meteorological models and their practical application followed very different paths. Lewis Fry Richardson could not figure out [5] that the equations he proposed could be solved in such a short time that it would be possible to anticipate (and therefore predict) atmospheric phenomena. The refinement and utility of meteorological models came hand in hand with the increase in the collection of meteorological data and advances in supercomputing until now, when we are able to anticipate the complex trajectory that a hurricane follows in its advance toward the...
The predictive power and application of epidemiological models, however, remained limited for many decades despite theoretical advances in refining them, since, as in the case of meteorology, it was necessary to collect data about the system in which pathogens spread. In this regard, capturing relevant data was much more elusive than in the case of meteorology, as it is human behavior that underlies the infection patterns that result in the observed epidemic curves.

The arrival of the XXI century brought this information with it. The democratization of the internet and the advances in the capture and resolution of data on human activity have allowed us to access and describe the skeleton of interactions through which infectious diseases are transmitted. Thus, in the last two decades great effort has been invested to incorporate epidemic models ingredients such as the complexity of contact networks, human mobility patterns at different geographic scales, and the time scales associated with human interactions. These data forced to reformulate the classical epidemiological models that, although they had already been refined in their compartmental structure far beyond the pioneering SIR one, still harbored simplistic hypotheses about the nature of interactions within the population.

With this information at hand, theoretical and computational tools from complex systems and network science can be used to analyze epidemiological problems and develop forecasting frameworks that integrate advanced epidemiological models with massive amounts of real demographic, mobility and socioeconomical data.

The methods and models of network epidemiology have played a prominent role in the scientific gear dedicated to fighting COVID-19. In our case, together with the group of Alex Arenas at the University Rovira i Virgili in Tarragona, we made use of our recent progresses on the formulation of multi-scale metapopulation models that integrate demographic data, age-structured contacts and recurrent mobility patterns [6–8] to construct a framework tailored for evaluating the propagation of the SARS-CoV-2 in Spain [9]. The first results were made public on February 28 in the form of a map, see figure 1, which projected, from the first imported cases and for the situation without containment measures, the evolution of the epidemic risk in different municipalities. The rapid increase in infections in different areas of the country was verified two weeks later when the first containment measures were applied. We also used our model to analyze which regions were on the verge of saturation in the capacity of the health system, projecting the evolution of the occupation of ICU beds. This study led us to directly advise the Spanish government on the need for an immediate total lockdown [10], which finally occurred on April 30. After this initial stage, the framework has evolved in parallel to the epidemic, both to advise specific epidemiological problems on the lifting of containment measures [11] and to develop formalism in other countries, such as Colombia, with different socioeconomic variables.

This and other recent experiences show that, although it is necessary to improve and refine our current models and facilitate the access to social and epidemiological data in real time, the advances and models generated in the field provide with a powerful tool to the public health systems to combat COVID-19 and future epidemics.

References