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Agent-based computational models to explore diffusion of medical innovations among cardiologists

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Background: Diffusion of medical innovations among physicians rests on a set of theoretical assumptions, including learning and decision-making under uncertainty, social-normative pressures, medical expert knowledge, competitive concerns, network performance effects, professional autonomy or individualism and scientific evidence.

Objectives: The aim of this study was to develop and test four real data-based, agent-based computational models (ABM) to qualitatively and quantitatively explore the factors associated with diffusion and application of innovations among cardiologists.

Methods: Four ABM were developed to study diffusion and application of medical innovations among cardiologists, considering physicians' network connections, leaders' opinions, "adopters' categories", physicians' autonomy, scientific evidence, patients' pressure, affordability for the end-user population, and promotion from companies.

Results: Simulations demonstrated that social imitation among local cardiologists was sufficient for innovation diffusion, as long as opinion leaders did not act as detractors of the innovation. Even in the absence of full scientific evidence to support innovation, up to one-fifth of cardiologists could accept it when local leaders acted as promoters. Patients' pressure showed a large effect size (Cohen's $d > 1.2$) on the proportion of cardiologists applying an innovation. Two qualitative patterns (speckled and granular) appeared associated to traditional Gompertz and sigmoid cumulative distributions.

Conclusions: These computational models provided a semiquantitative insight on the emergent collective behavior of a physician population facing the acceptance or refusal of medical innovations. Inclusion in the models of factors related to patients' pressure and accesibility to medical coverage revealed the contrast between accepting and effectively adopting a new product or technology for population health care.

1. Introduction

It is commonly accepted that diffusion of innovations is often driven by social contagion or imitation [1]. Specifically, diffusion of medical innovations among physicians rests on a set of theoretical assumptions, including learning and decision-making under uncertainty, social-normative pressures, medical expert knowledge, competitive concerns, network performance effects, professional autonomy or individualism, and scientific evidence [2]. The process of propagation and adoption of medical innovations is not only relevant for marketing research, but also because differences in the performance of medical care may be due to variation in the introduction, diffusion and acceptance of new practices [3–6].

Mathematical representation on the basis of Bass [4–7] or Gamma-Shifted Gompertz [1] models and local interaction models for social networks [8] were traditionally used to explore diffusion of innovations. Low-dimensional differential equations, aggregate regression analysis, and game theory methods are appropriate for some explanatory purposes; however, agent-based computational modeling (ABM) is the main tool in the analysis of spatially distributed systems with heterogeneous autonomous actors connected in social networks, particularly, when decision-making relies on restrained information and limited individual rationality or computing capacity [9]. In ABM, a system is designed as a collection of independent decision-making entities called agents, where each agent individually assesses its situation and makes decisions on the basis of a set of rules. An advantage of ABM

Abbreviations: ABM, agent-based computational modeling/agent-based model; CPGs, Clinical Practice Guidelines

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is that it computes repetitive competitive interactions between agents to explore population dynamics out of reach of traditional differential equation modeling [10]. As a tool for real-world empirical research, ABM can generate stable macroscopic patterns arising from local interaction of agents, known as emergent phenomena [9]. Agent-based computational modeling applies to cases where people are influenced by their social context, i.e. what others around them do; therefore, it can be used to model diffusion of ideas, products or innovations on social networks. Previously, only a few studies used the ABM approach to model diffusion of medical innovations. These studies provided support to the importance of social networks and external influences in the diffusion process [11], the effect of the interaction between patients and physicians to adopt a new technology [12] and the value of opinion leadership on adopting new evidence [13].

The aim of this study was to develop and test four real data-based ABM to qualitatively and quantitatively explore the factors associated with diffusion and application of innovations among cardiologists.

2. Material and methods

Four ABM were developed to study diffusion and/or effective use of medical innovations among cardiologists with real-world data. In this application of ABM to medical sociology, agents represented physicians, and agent relationships represented the processes of social interaction. For modeling purposes physicians were generally assumed to be the decision-makers in the system after local regulatory approval, peer opinion leaders were considered to be polymorphic (influential across a wide range of innovations), and no planned or intentional dissemination program was contemplated. Patients' pressure and their affordability or insurance coverage were also considered in the decision-making process to accept and use an innovation. An extra model explored the influence of promotional information provided by pharmaceutical companies on diffusion of innovations. The general steps for building the ABM were as follows [14]:

1. Identification of agent types (cardiologists and opinion leaders) and their attributes based on a theory of agent behavior (innovator, early adopter, early and late majority, laggard scale for cardiologists' profiles, and promoter-neutral-detractor scale for opinion leaders' profiles) [15,16].
2. Definition of the environment where agents interact with each other. The whole population of Argentine cardiologists was represented on a two-dimensional space, where behaviors and decisions were defined discretely (binary). Interactions among cardiologists were based on neighborhood criteria and on their relationship with opinion leaders.
3. Specification of agent interactions, namely, the methods that control which agents interact, when they interact, and how they interact during the simulation. Cellular automata principles were used to represent agent interaction patterns and available local information by using a two-dimensional grid where the cells immediately surrounding an agent were its neighborhood. Additionally, the network topology of opinion leaders influencing cardiologists was included to more accurately describe social agents' interaction patterns.
4. Specification of methods by which agent attributes are updated in response to agent-to-agent interaction. Agent-based models were built as cellular automata that simulated the spatial distribution of acceptance for a medical innovation by having each target agent take the "opinion" of its eight surrounding neighbors and opinion leaders; then, according to the sum of colleagues' opinions and leader position, the previously established degree of individual autonomy and the level of scientific evidence, the target agent decided to accept or refuse the innovation.
5. Implementation of the ABM in computational software. ABM models were implemented with NetLogo (version 4.1.2, Northwestern University, Evanston, IL) [17].

Table 1
Parameter values used in models simulation.

Parameters	Values (95% CI)[18,22,30–31]
Population of cardiologists	8100
Distribution of Rogers' profiles among cardiologists:	
innovators	6.0% (4.0–8.0%)
early adopters	52.7% (48.5–56.9%)
early majority	20.3% (16.9–23.7%)
late majority	17.6% (14.4–20.8%)
laggards (traditionalists)	3.4% (1.9–4.9%)
Giant component of the cardiologists'social network	41.0% (36.8–45.2%)
Degree of cardiologists' professional autonomy	59.0% (54.8–63.2%
Percentage of the cardiologists' network influenced by:	
one top local opinion leader	28.5% (24.7–32.3%)
two top local opinion leaders	33.5% (29.5–37.5%)
three top local opinion leaders	37.0% (32.9–41.1%)
four top local opinion leaders	44.0% (39.8–48.2%)
Percentage of physicians and leaders changing opinion over time	0.1%
Distribution of cardiologists' opinions regarding timing and conditions for accepting a new drug:	
just when the drug appears on market	4.5% (2.7–6.3%)
when the drug is used by a minority of colleagues	4.3% (2.6–6.0%)
when the drug is used by 50% of colleagues	7.5% (5.3–9.7%)
when the drug is used by most colleagues	4.5% (2.7–6.3%)
when the drug has a fully tested utility	79.2% (75.8–82.6%)
Rate of Clinical Practice Guideline utilizationby cardiologists	91.5% (89.2–93.8%)
Patients trusting only in doctors to obtain information	81.7% (78.9–84.5%)
Patients giving much importance to Internet information	7.5% (5.6–9.4%)
Local population with formal medical coverage	63.9%
Percentage of population with public medical insurance	77.0%
Estimated usage rate of innovations in the public sector	0.50

CI, confidence interval.

6. The model is run to analyze the output from the standpoint of linking the agents' micro-scale behaviors to the macro-scale behaviors of the system.

In a previous study, we conducted a survey to build a social network of cardiologists, where they were asked to individualize local opinion leaders among them [18]. Additionally, cardiologists were classified as having from an innovative to a conservative behavior based on classical reports of Ryan & Gross [15] and Rogers [16]. Rogers' diffusion of innovations theory explains how an idea or product gains momentum and diffuses through a specific population or social system over time. The end result of this diffusion is that people, as part of a social system, adopt a new idea, behavior, or product. For the implementation of the first ABM model, data on the network topology and Rogers' cardiologist profiles, as well as their opinions on accepting medical innovations were taken from the previously mentioned survey (Table 1). We applied a threshold model considering that physicians adopt the new idea or product as soon as the utility of the medical innovation, or its acceptance by colleagues, exceeds some critical level or threshold. Regarding Rogers' adoption profiles, it was considered that the possibility of innovation acceptance by cardiologists increased from laggards to innovators (acceptance gradient), since it was easier for innovators than for laggards to accept new ideas or products. Also, the model assumed that local top leader's opinions could speed or slow down the process of spreading innovations into a medical community by influencing the local physicians' network according to the number of connections. Leader opinion was classified as promoter, neutral or detractor regarding its position with respect to the medical innovation. The degree of professional autonomy for individual decision was obtained from the proportion of cardiologists that did not select any opinion leader as a guide to follow. The potential for cardiologists and leaders to change their opinion over time was modeled by adding a random parameter