Social Science & Medicine 125 (2015) 51–59

Contents lists available at ScienceDirect

Social Science & Medicine

journal homepage: www.elsevier.com/locate/socscimed

Reprint of: Results from using a new dyadic-dependence model to analyze sociocentric physician networks☆

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ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form
30 June 2014
Accepted 6 July 2014
Available online 7 October 2014

Keywords:
Dyadic independence
Latent variables
Patient sharing
Physician influence
Sociocentric network
Transitivity

ABSTRACT

Professional physician networks can potentially influence clinical practices and quality of care. With the current focus on coordinated care, discerning influences of naturally occurring clusters and other forms of dependence among physicians' relationships based on their attributes and care patterns is an important area of research. In this paper, two directed physician networks: a physician influential conversation network ($N = 33$) and a physician network obtained from patient visit data ($N = 135$) are analyzed using a new model that accounts for effect modification of the within-dyad effect of reciprocity and inter-dyad effects involving three (or more) actors. The results from this model include more nuanced effects involving reciprocity and triadic dependence than under incumbent models and more flexible control for these effects in the extraction of other network phenomena, including the relationship between similarity of individuals' attributes (e.g., same-gender, same residency location) and tie-status. In both cases we find extensive evidence of clustering and triadic dependence that if not accounted for confounds the effect of reciprocity and attribute homophily. Findings from our analysis suggest alternative conclusions to those from incumbent models.

1. Introduction

Professional physician social networks play a pivotal role in the diffusion of knowledge and adoption of new clinical practices (Burt, 1987; Coleman et al., 1966; Fennell and Warnecke, 1988; Nair et al., 2008; Valente, 1996). Understanding the topology and structure of physician professional networks in which ties between physicians depict potential information-sharing relationships can provide insights into how physician beliefs, behaviors and preferences are shaped. It may also reveal improved strategies for the spread of medical and healthcare information (West et al., 1999). To give a few examples: There is evidence suggesting that the structure of physician networks could be a factor underlying the cost and intensity of care in US hospitals (Barnett et al., 2012); Transfers from a peripheral to a more centralized hospital in a critical care network have been found to improve patient outcomes and survival through more efficient care (Iwashyna et al., 2009); Collaborations between physicians across specialties appears important to implementing therapeutic support protocols (Trzeciak et al., 2006); Physicians appear to rely mostly on their colleagues for information and advice about the care of their patients (Keating et al., 2007); Algorithms that detect naturally occurring "clusters" of physicians may be a basis for forming accountable care organizations (ACOs) (Landon et al., 2013).

In many of the above examples, physician networks have previously been studied using dyadic independent models that relate the probabilities of relationships existing between physicians (ties) to structural features of networks such as density, reciprocity (the phenomena whereby mutual relationships between physicians occur more commonly than by chance), and the distribution of the physician's number of connections (degree) while accounting for heterogeneity between physicians (Keating et al., 2007; Landon et al., 2012). However, these and simpler models fail to account for higher-order effects that account for clustering of ties within groups of three or more physicians and phenomena such as

DOI of original article: http://dx.doi.org/10.1016/j.socscimed.2014.07.014.

☆ The article is reprinted here for the reader's convenience and for the continuity of the special issue. For citation purposes, please use the original publication details: Social Science & Medicine 117 (2014) 67-75.

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http://dx.doi.org/10.1016/j.socscimed.2014.08.027
0277-9536/

transitivity ("a friend of a friend is a friend"). Statistical models that identify such effects have the potential to better inform research on the coordination of health care. In addition, determining whether the effects of reciprocity and homophily of physicians' attributes are modified by phenomena such as transitivity may reveal mechanisms for achieving faster diffusion of information and improved quality and cost of healthcare.

In this paper we analyze two sociocentric networks of physicians' professional relationships. The first network is a binary network of influential discussions on women's health issues among physicians in a hospital-based practice. The second uses overlap of physicians patient cohorts to construct a network of professional relationships between physicians in a large geographical region. In both, the goal is to determine whether the effect of reciprocity differs between regions of the network with high and low prevalence of ties, and to estimate the independent effect of the similarity of physicians' characteristics and of their attributes (whose effects constitute homophily) on their professional relationships.

The remainder of the paper is as follows. Below, we provide background material. In Section 2 we review and develop models while Section 3 describes estimation methods. In Section 4 we apply our model to a physician influential conversation network from a Boston teaching hospital and a network of physicians formed on the basis of sufficient overlap of their patient cohorts from the North Dakota hospital referral region (HRR). An extensive discussion of results for both models follows. The paper concludes in Section 5.

1.1. Sociological background

Sociocentric networks consist of collective information on the status of connections or "ties" between actors, often embedded within a complex social structure. The collection of physician "dyads", "triads", and other "clusters" in a physician network inform the social structure of a hospital or physician practice. Ignoring the hierarchy of social dependence (e.g. individual, dyadic, triadic) can lead to biased estimates of the effects of lower-level network features (e.g. within dyad features such as reciprocity). Recent analyses of physician networks have begun to focus on different aspects of the underlying social structure in addition to the actor-specific attributes as a means to understanding the behavior of the network as a whole (Lomi and Pallotti, 2012; Zappa, 2011). This has important implications for knowledge transfer and patient referrals; e.g., in a network with overlapping clusters or groups, information is more likely to diffuse faster than if the network contained non-overlapping groups. Similarly, the positioning of physicians can help explain patterns of ties and identify stochastic equivalence classes within the network, which in turn may provide valuable information about where best to seed a network-based intervention (e.g., coupons to purchase healthy living products) and the diffusion of information across the network (Hanneman and Riddle, 2005).

1.2. Network and statistical background

A common way of modeling sociocentric data is using p^* (exponential-family random graph) models (Frank and Strauss, 1986; Wasserman and Pattison, 1996). These treat the network as a single observation. An alternative model to the p^* model is developed from the premise of treating dyads as independent or conditionally independent random variables (Fienberg et al., 1985; Holland and Leinhardt, 1981; Yang and Yong, 1987). For example, the p_2 model for directed networks assumes dyadic independence conditional on actor specific random effects (van-Duijn et al., 2004). This approach is appealing as the dyad is the largest component of a sociocentric network such that knowing the status of one component does not restrict the possible states of any other component. Consequently, the conditional independence structure allows the model for the network to be induced from the model for a single dyad, ensuring desirable statistical properties (O'Malley, 2013).

Clustering induced by groups of ≥ 3 actors such as transitivity, stochastic equivalence, and structural balance are of great interest in characterizing the underlying social structure of the physician networks. Yet, it is only recently that conditionally dyadic independence models that include such terms have been developed (e.g., Nowicki and Snijders, 2001; Hoff, 2005; Hoff et al., 2002). In related work, we combined the desirable features of the p_2 and p^* models to develop a longitudinal p_2 model that includes transitivity and other forms of between-dyad dependence as lagged terms (Paul and O'Malley, 2013). The latter model was notable because the dyad is the unit of analysis and reciprocity is the direct effect of the status of the tie $j \rightarrow i$ on the tie $i \rightarrow j$, arguably providing a more direct and intuitive measure of reciprocity. However, to date conditionally dyadic approaches are restrictive in that the effects of reciprocity and triadic dependence were assumed to be additive (no interaction between them).

2. Methods

In this section we adapt the longitudinal model we developed previously with the bilinear mixed effects (BME) model of Hoff (2005) to accommodate triadic dependence and other forms of between-dyad clustering in a cross-sectional network. Therefore, unlike the BME models developed by Hoff in which tie-status is the unit of analysis, under the resulting "extended p_2 model" (referred to as EP2 henceforth) developed here the dyad is the unit of analysis and reciprocity is the effect of an observed variable. This formulation allows more nuanced effects of reciprocity and more flexible adjustment for tie dependence in the network.

2.1. The p_2 model for sociocentric data

We first overview the p_2 model (see (van-Duijn et al., 2004) for a more detailed description than the following). Let $Y_{[nxn]}$ be an adjacency matrix of connections (ties) between n actors in a directed binary network whose ijth entry denotes the status of the relationship from i to j. The probability function representing the status of the dyad involving actors i and j, (Y_{ij}, Y_{ji}), is given by:

$$\Pr\left((Y_{ij}, Y_{ji}) \middle| \theta, \rho\right) = \text{gen.logit}^{-1}\left(\theta_{ij} y_{ij} + \theta_{ji} y_{ji} + \rho_{ij} y_{ij} y_{ji}\right), \quad (1)$$

where $\theta_{ij} = \mu_{ij} + \alpha_i + \beta_j$ and gen.logit denotes the generalized logit link function that transforms the dyad state-probabilities such that they can be related to a linear function of predictors. The parameter μ corresponds to density, ρ to reciprocity, and α and β to "gregariousness" (propensity of an individual to like others - in the sense of forming ties) and "popularity" (propensity of an individual to be liked by others) of the actors, respectively. The heterogeneity of the density and reciprocity parameters in (1) allows these effects to vary in magnitude across the network with actor-, dyad-, and tie-level covariates. The actor specific effects (α_i, β_i) are assumed to be random variables drawn from a bivariate normal distribution with mean (0, 0), variances σ_α^2 and σ_β^2, and correlation $\rho_{\alpha\beta}$.

In (1) the status of Y_{ij} depends on $\rho_{ij} Y_{ji}$ on the logit-scale; the log-odds of $Y_{ij} = 1$ increases by ρ_{ij} if $Y_{ji} = 1$. The correlation $\rho_{\alpha\beta}$ is subtly different from reciprocity as it represents the extent that gregarious physicians are also attractive physicians. The assumption of conditional independence between dyads given the vectors of random