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METHODS ARTICLE

# Mapping Physician Networks with Self-Reported and Administrative Data

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**Objective.** To assess whether connections between physicians based on shared patients in administrative data correspond with professional relationships between physicians.

**Data Sources/Study Setting.** Survey of physicians affiliated with a large academic and community physicians' organization and 2006 Medicare data from a 100 percent sample of patients in the Boston Hospital referral region.

**Study Design/Data Collection.** We administered a web-based survey to 616 physicians (response rate: 63 percent) about referral and advice relationships with physician colleagues. Relationships measured by this questionnaire were compared with relationships assessed by patient sharing, measured using 2006 Medicare data. Each physician was presented with an individualized roster of physicians' names with whom they did and did not share patients based on the Medicare data.

**Principal Findings.** The probability of two physicians having a recognized professional relationship increased with the number of Medicare patients shared, with up to 82 percent of relationships recognized with nine shared patients, overall representing a diagnostic test with an area under the receiver-operating characteristic curve of 0.73 (95 percent CI: 0.70–0.75). Primary care physicians were more likely to recognize relationships than medical or surgical specialists ($p < .001$).

**Conclusions.** Patient sharing identified using administrative data is an informative "diagnostic test" for predicting the existence of relationships between physicians. This finding validates a method that can be used for future research to map networks of physicians.

**Key Words.** Physician networks, physician referral, health care systems, network analysis

Relationships between health care providers are essential to a functioning health care system. Physicians rely on their relationships with physician colleagues for patient referrals (Gonzalez and Rizzo 1991), clinical advice (Keating, Zaslavsky, and Ayanian 1998), and information about the latest clinical advances (Gabbay and le May 2004). Given their importance, understanding the nature of such relationships could yield valuable knowledge

about the emergence of local practice patterns and the diffusion of health care practices. This understanding could in turn inform health policy decisions aimed at modifying physicians' behavior.

Since every doctor has a range of interactions with an array of other doctors, physicians are embedded within a network of relationships, or ties, with their physician colleagues. Using tools from the emerging field of complex network analysis (Newman 2003), physician professional networks defined by such formal or informal relationships can be analyzed at a deeper level than previously possible. Some studies have already begun using these methods to analyze health care networks, addressing topics such as the exchange of clinical advice, the diffusion of pharmaceutical use, or organizational performance and cost-efficiency (Keating et al. 2007; Christakis and Fowler 2010; Iyengar, Van den Bulte, and Valente 2010).

A major hurdle to studying physician networks is the lack of data on physician relationships which limits the scope of many studies. For instance, Keating and colleagues studied information seeking among primary care physicians (PCPs) about issues related to women's health, but they studied only 38 doctors whom they surveyed personally. Such de novo survey work requires laborious ascertainment of each relationship among pairs of doctors to map a relationship network, which is a formidable barrier to replication across multiple hospitals or practices.

One potential way to identify physician relationships would be to use records regarding patients shared between physicians, as identified in administrative databases. Furthermore, using shared patients to define relationships is clinically intuitive. Physicians often email, phone, or "curbside" a colleague with specific clinical questions or cases, and these informal requests for information are formalized when the patient is actually referred for care

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(Keating, Zaslavsky, and Ayanian 1998). Thus, the presence of shared patients in administrative data—arising because of referral, patient self-selection, administrative rules (e.g., insurer policies regarding second opinions), or even chance—may represent an important source of information about physician relationships that could be useful for large-scale studies using the tools of network science.

In this study, we sought to validate the use of patient sharing identified in administrative data as a source of information on physician networks. To do so, we first identified physicians connected via shared patients in Medicare data. We then surveyed physicians in a large physicians' organization and asked them about their referral and information-sharing relationships with other physicians and evaluated the correspondence between those relationships and patient sharing measured by Medicare claims.

## METHODS

### *Survey Participants*

We surveyed physicians who were members of a physicians' organization associated with a large academic medical center and several outlying community hospitals. The cohort included physicians in office-based patient care specialties (excluding anesthesiologists, emergency medicine, radiologists, and pathologists) who were affiliated with the physicians' organization in 2006 and who filed Medicare claims in 2006. The last two restrictions were applied because we used data from 2006 Medicare claims as our source of administrative data on patient sharing. Using these criteria, we identified 616 office-based patient care physicians in the physicians' organization who filed Medicare claims in 2006, and thus were eligible to participate in our study.

### *Survey Administration*

We mailed to each physician a letter containing an invitation to the web-based survey that included a short URL web address and a personalized password to access the survey instrument. The mailing included a U.S. $5 bill and a privacy statement from the Centers for Medicare and Medicaid Services. One week after the mailing, physicians who had not responded to the survey were sent a reminder e-mail with a link to the survey, followed a week later by a second reminder e-mail to remaining nonrespondents. Nonresponding physicians were contacted by phone to verify that the survey mailings had been received,

encourage participation, and offer to e-mail another link to the survey. The survey was designed and implemented using KeySurvey (http://www.keysurvey.com) and was administered from February through June of 2010.

*Survey Instrument*

The survey instrument was designed to elicit information about the information-sharing and referral relationships of respondents with other physicians of any specialty. In the first section of the survey, we used a set of "name generator" (a term used in the sociological literature for survey questions eliciting social contacts) questions (Vehovar, Lozar Manfreda, and Koren 2008): we first asked respondents to identify three specialties to whom they "most commonly refer," "receive referrals from," or "whom your patients commonly see, whether or not you referred them." These response options were chosen to encompass the diversity of patient-sharing relationships among physicians. Respondents were then prompted to provide up to two names of physicians in each of the three specialties to whom they most commonly referred patients or received patient referrals from. Respondents also had the option of saying that they had a referral relationship with "no specific" physician in a specialty. This option was included to account for the situation where a physician refers a patient to a specialty practice or hospital department without an individual physician in mind. After providing these names, the respondents were asked whether they *shared advice* or made *patient referrals* with each of the physicians by choosing any of the options shown in Table 1(A).

Next, we presented respondents with an individualized "roster," or prespecified list (in contrast to the respondent-generated list of physician names in the "name generator" section), of 20 physicians from any office-based patient care specialty. The physicians' names presented to each respondent were chosen from among physicians with whom the respondent shared Medicare patients in 2006. Using all Medicare data for a 100 percent sample of patients living in the Boston hospital referral region (Dartmouth Medical School and Center for the Evaluative Clinical Sciences 1996) during 2006, we identified a relationship (tie) between two doctors if they each had a significant encounter with one or more common patients. We included in our analyses patients enrolled in Medicare Part A and Part B, and we excluded patients enrolled in capitated Medicare Advantage plans because they lacked detailed claims information. We defined significant encounters

Table 1: Relationship Categories in Survey Instrument

| (A) Name Generator Options | (B) Roster Options |
|---|---|
| **Question:** *For the physicians you named in the last question, please select all of the options that apply below:* | **Question:** *Please check all the boxes that apply to indicate your relationship with each physician listed below:* |
| ***Referral*** | ***Referral*** |
| "I refer patients to this physician." | "I refer patients to him/her." |
| "I receive referrals from this physician." | "I receive referrals from him/her." |
| | "We share patients but don't refer to each other." |
| ***Advice*** | ***Advice*** |
| "I seek out this physician for informal clinical advice." | "I seek him/her out for informal clinical advice." |
| "This physician seeks me out for informal clinical advice." | "He/she seeks me out for informal clinical advice." |
| | ***Other*** |
| | "Member of my practice." |
| | "None of these options apply." |

based on the presence of a CPT code for a face-to-face office or hospital visit or a meaningful procedure code with an RVU value of at least 2 to capture bundled encounters where an evaluation and management service might not be billed. The "strength" of a relationship between two physicians was determined by the number of patients they shared in 2006. Overall, we studied claims for 46,937 Medicare patients treated by the 616 physicians in our cohort.

To construct each respondent's individual roster of 20 physicians for the survey, we first selected 16 physicians who were linked to the respondent through shared Medicare patients. Because the majority of ties between physicians were created by only one shared patient, we sampled ties of different strengths to ensure a wide range of tie strengths in each respondent's roster. For each respondent, we randomly sampled from their shared-patient connections four ties to other physicians of strength 1, four ties of strength 2, four ties of strength 3 or 4, and four ties of strength 5 or greater. To complete the roster, we randomly chose four physicians within the physicians' organization with whom the respondent shared *no* Medicare patients in 2006 as a negative control. Respondents were asked to check all applicable responses in seven possible categories, shown in Table 1(B), that could describe their relationship with the listed physicians.

Finally, respondents were asked to provide basic demographic and medical practice information.

*Statistical Analysis*

We compared respondents and nonrespondents according to key demographic characteristics from the 2006 American Medical Association Masterfile in addition to specialty and hospital affiliation data provided by the physicians' organization whose members were surveyed. We defined physicians as PCPs if their primary specialty was internal medicine (with no additional subspecialty), family medicine, general practice, preventive medicine, geriatrics, or general osteopathy. All other physicians were classified as medical or surgical specialists, or "other" (e.g., psychiatry). To assess differences between the characteristics of respondents and nonrespondents, we used $\chi^2$ and *t*-tests, as appropriate. We compared the names given by respondents in the name generator section of the survey to patient-sharing relationships in Medicare data by first matching the names with the 2006 Medicare Provider Identification File to obtain Unique Physician Identifier Numbers (UPINs) for the named physicians. The pairs of respondents and named physicians were then compared with all patient-sharing relationships identified in the Medicare claims database based on claims for 100 percent of Medicare patients residing in the Boston hospital referral region. We assessed differences in proportions of relationships recognized by respondents using the two-proportion *z*-test with Yates' continuity correction (Pagano and Gauvreau 2000).

The "number of patients shared" based on administrative data can be thought of as a diagnostic test for the existence of a reported relationship between two physicians. Given this, we calculated a receiver-operating characteristic (ROC) curve for predicting physician reported relationships based on the number of patients shared. To assess overall predictive accuracy, we computed the area under the ROC curve and its standard error by adapting Harrell's *c* statistic as calculated using the *rcorr.cens* function in the *Hmisc* package (version 3.8-2) implemented in the *R* statistical programming language (Hanley and McNeil 1982; Newson 2006; Harrell Jr. 2010) To visualize the network of physicians based on the relationships measured using administrative data and reported in the survey sample, we used the Kamada–Kawai algorithm as implemented in the *igraph* package in R (Kamada and Kawai 1989; Csardi and Nepusz 2006). All tests of statistical significance were two-sided. All analyses were conducted using *R* statistical software, version 2.11.1 (R Development Core Team 2009). The study protocol was approved by the Harvard Medical School Committee on Human Studies.

# RESULTS

## *Characteristics of Respondents, Nonrespondents and Their Physician Networks*

Of the 616 physicians contacted, we received 386 responses for an overall response rate of 63 percent. Nine other respondents had incomplete responses from the physician roster and were excluded from the analysis dataset. Respondents and nonrespondents were similar in terms of sex (Table 2).

Table 2: Characteristics of Respondents and Nonrespondents

| | *N (%)* | | |
|---|---|---|---|
| | *Respondents** | *Nonrespondents** | *p-value* |
| Total | 386 | 230 | |
| Sex | | | |
| Male | 262 (68) | 163 (71) | .49 |
| Female | 124 (32) | 67 (29) | |
| Race[†] | | | |
| White | 323 (84) | NA | |
| Nonwhite | 62 (16) | | |
| Hospital | | | |
| Academic center | 340 (88) | 179 (78) | <.001 |
| Other | 46 (12) | 51 (22) | |
| Specialty | | | |
| PCP | 107 (28) | 42 (18) | .055 |
| Medical | 157 (41) | 110 (48) | |
| Surgical | 96 (25) | 64 (28) | |
| Other | 26 (7) | 14 (6) | |
| Years since medical school graduation | | | |
| Mean | 26 | 29 | <.001 |
| Median | 24 | 27 | |
| IQR | 16–34 | 21–37 | |
| Practice size[†] | | | |
| Solo or 2-person | 54 (14) | NA | |
| 3–10 physicians | 125 (33) | | |
| 11–50 physicians | 129 (34) | | |
| >50 physicians | 74 (19) | | |
| Clinical days per week[†] | | | |
| 0–1 | 104 (27) | NA | |
| 1.5–3 | 130 (34) | | |
| 3.5 or more | 148 (39) | | |

*Notes.* *p*-values calculated using a two-sample *t*-test or $\chi^2$ test, as appropriate.

*Respondent characteristics taken from survey responses for respondents and from AMA Masterfile or physicians' organization database for nonrespondents.

[†]Race was missing for one respondent, practice size for four respondents, and clinical days per week for four respondents. Missing data were not included in calculations of percentages.

IQR, interquartile range; NA, data not available; PCP, primary care physician.

Nonrespondents were less likely to be PCPs, though the difference between groups was at the threshold of statistical significance ($p = .055$). In addition, nonrespondents were more likely to be affiliated with a hospital outside of the main academic medical center associated with the physicians' organization ($p < .001$) and had more years since graduating medical school ($p < .001$). Overall, the sample of respondents was 68 percent male and mostly composed of medical specialists (41 percent), though primary care providers and surgical specialists (including general surgeons) were well represented in the sample (28 and 25 percent, respectively).

The distribution of number of connections measured for respondents and nonrespondents to other physicians in the Boston hospital referral region through patient sharing and the strength of those ties (e.g., 1, 2, or more patients shared) are shown in Figures SA1 and SA2. Figure SA1 shows the maximum number of relationships which we could identify for each physician eligible for this study, from which we sampled the relationships used in our survey.

*"Name Generator" Results*

In the first section of the survey, respondents were asked to name up to 2 physicians in up to 3 specialties selected by the respondent with whom they have referral relationships. Physicians reported a median of 3 specialties (the maximum possible) and provided a median of 4 physician names (out of 6 possible), resulting in a total of 1,328 physician names. We next assessed whether these named physicians were linked to respondents in our Medicare data. Of the 1,328 names given, 59 could not be matched to Medicare UPINs, usually because the provider was too recently licensed to be assigned a UPIN, which was replaced in 2007 by the National Provider Identifier system (Caldwell 2003). This left 1,269 named physicians, of which 67.9 percent, or 862, were linked to the respondent by the sharing of one or more Medicare patients in 2006 (the remainder of identified doctors were ones with which the respondent did not share Medicare patients in 2006).

There was no significant difference in the proportion of named physicians linked to respondents who were affiliated with the academic medical center versus other hospitals ($p = .49$, results not shown), though there was a statistically significant difference in the proportion of physicians linked to respondents depending on the specialty of the respondent ($p < .001$, results not shown). Overall, surgeons were less likely to have their named colleagues identified as patient-sharing relationships in the Medicare data (only 19

percent of matched relationships came from surgeon respondents versus 31 percent of unmatched relationships from surgeons).

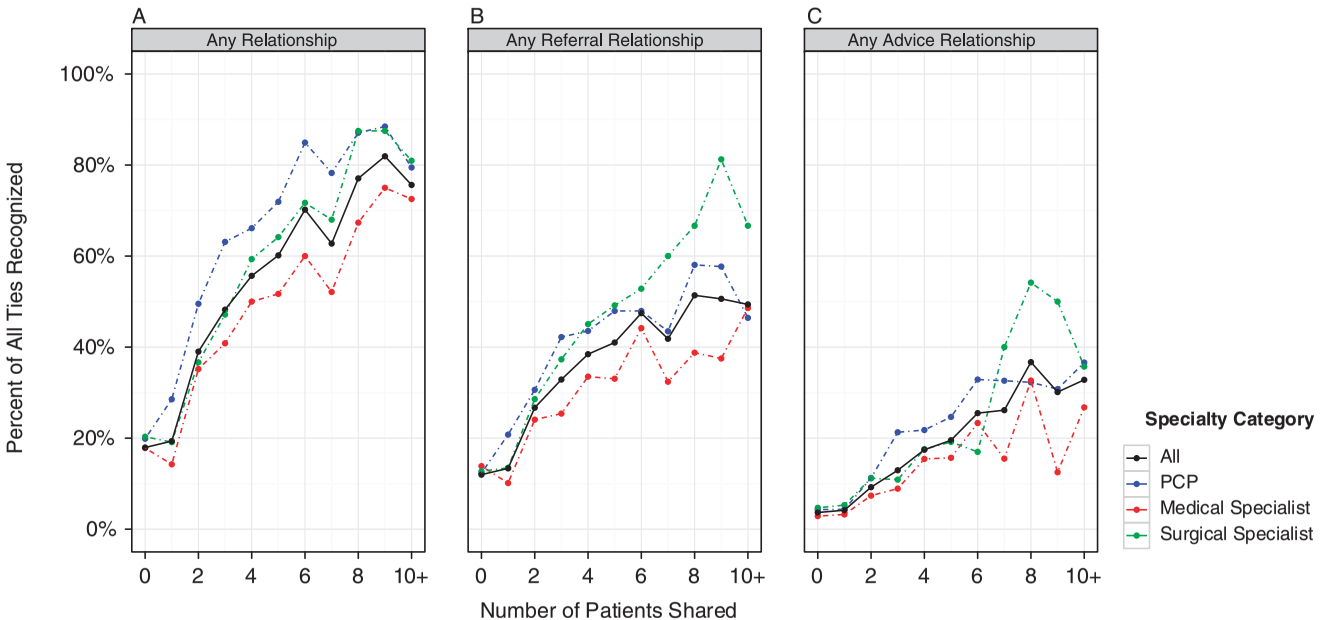
We also examined whether named physicians linked to respondents through Medicare patients were more or less likely to be affiliated with the same hospital. We found that matched physicians pairs were more likely to be in the same hospital than nonmatched pairs (82 percent of matched pairs in same hospital versus 53 percent of unmatched pairs, $p < .001$). Some data on hospital affiliations of named physicians were missing (12 percent of unmatched pairs were missing hospital affiliation for the named physician), but the statistically significant difference would hold even if all missing unmatched pairs were from the same hospital.

### *Physician Roster Results*

In the next section of the survey, we used a roster format wherein each doctor was presented with candidate physicians that they might know. We assessed 7,720 possible relationships identified for these 386 respondents, 20 relationships per respondent, based on shared Medicare patients with other doctors. The probability that a respondent recognized a physician listed in the roster as a colleague through *advice*, *referral*, *sharing patients*, or *sharing a practice* increased strongly with the number of Medicare patients shared in 2006 (Figure 1). The overall sample size of total relationships for each level of patients shared ranged from 1,695 ties for relationships with zero patients shared down to 83 ties for nine patients shared. The proportion of ties to physicians recognized by respondents as having any relationship increased from 18 percent and 19 percent for ties with zero and one patients shared, respectively, to a plateau of 82 percent with nine patients shared ($p < .001$ for difference of proportion at nine patients shared with proportions at zero and one patients shared) (Figure 1A). The area under the curve for using shared patients to predict any connection between two physicians was 0.73 (95 percent CI: 0.70–0.75) (Figure 2; full information on sensitivity, specificity, negative and positive predictive values across a range of thresholds is given in Table SA1).

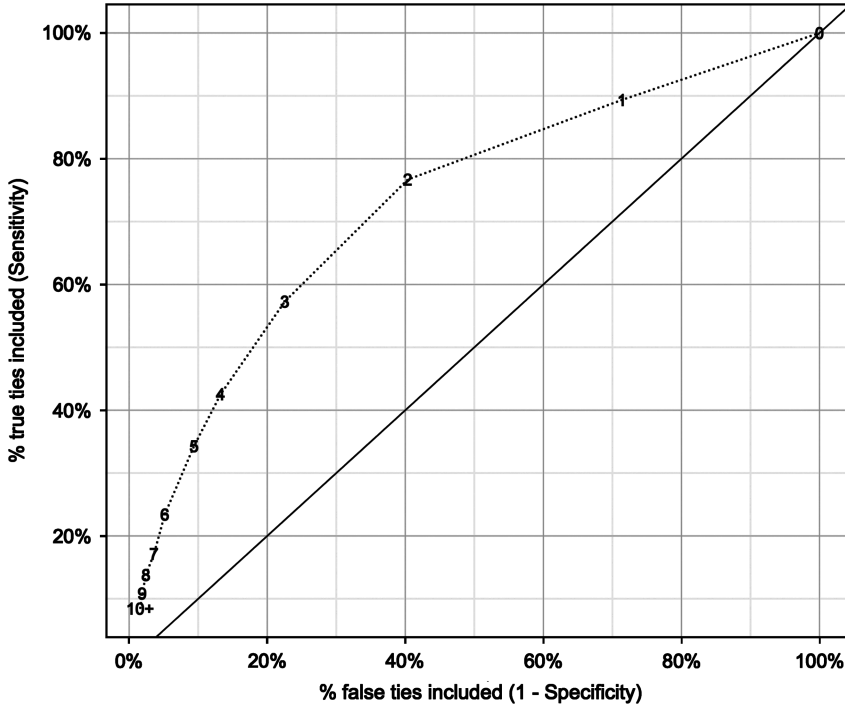
We next looked at the specific types of relationship. Similar to the associations for *any relationship*, discussed above, the proportion of ties recognized as *referral relationships* increased from 12.0 percent for ties with zero patients shared to a peak of 51 percent for ties with eight patients shared ($p < .001$) (Figure 1B). Ties recognized as *advice relationships* showed a similar trend as well, with 3.7 percent ties with zero patients shared recognized increasing up to 37 percent recognized for ties with eight patients shared ($p < .001$) (Figure 1C).

Figure 1: Probability That Respondents Identified a Relationship to a Listed Physician by Number of Patients Shared




This figure shows the proportion of ties to physicians that respondents identified as true relationships based on the number of Medicare patients shared in 2006. The x-axis represents the number of patients shared for a group of ties in the Medicare data and the y-axis shows the proportion of all ties of the strength on the x-axis that were identified by respondents as either having any connection (A), any referral relationship (B), or any advice relationship (C). Because of small sample sizes of ties above 10 patients shared, all ties with a value of 10 or more patients shared are included in the "10+" level on the x-axis.

Figure 2: Receiver Operating Characteristic Curve for Existence of Any Relationship between Physicians




ROC curve (dotted line) for identifying any relationship between two physicians based on the number of shared Medicare patients in 2006. Number labels show the point on the ROC curve corresponding to each possible cutoff of Medicare patients shared during 2006 up to 10 or more patients shared. The solid line shows a line of slope 1 (or the ROC curve for a diagnostic test no better than chance) as a guide. The area under the curve of this ROC curve (or *c* statistic) is 0.73, 95 percent confidence interval: 0.70–0.75.

### *Examining Relationships by Physician Specialty and Other Factors*

There were clear differences between the proportions of relationships recognized across different levels of patient-sharing when considering the specialty of the respondents. Among relationships where any connection was measured in the claims data (Figure 1A), significantly more relationships were recognized by PCPs than by medical specialists. Taking all ties of strength 1 or greater, PCPs recognized 55 percent of 1,677 total relationships, significantly

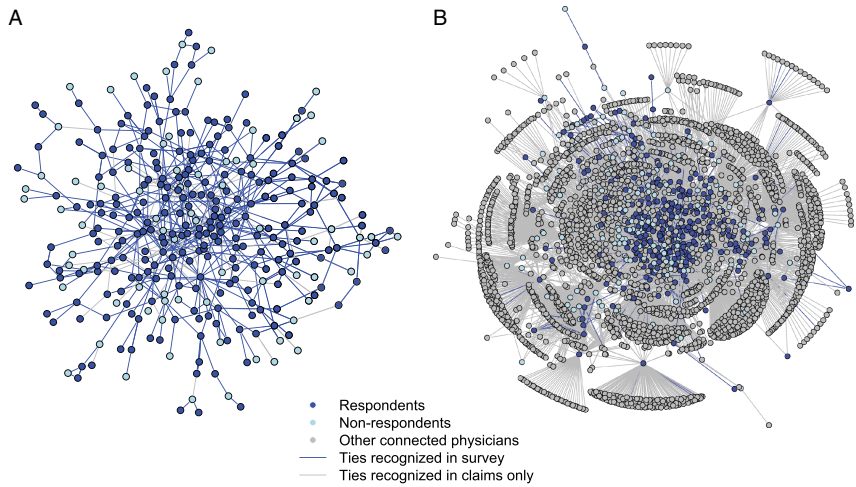
more than the 38 percent of 2,512 relationships recognized by medical specialists ($p<.001$) and 39 percent of 1,472 relationships acknowledged by surgeons ($p<.001$). Significant differences between the proportion of relationships recognized by PCPs versus medical specialists ($p<.01$) were also observed when we conditioned on each subset of relationships with strength of one through seven patients shared (depicted in Figure 1A). In addition, respondents recognized different proportions of colleagues depending on the total number of connections they had to other physicians in the Boston hospital referral region, with respondents in the lowest tertile of number of connections in general recognizing more of their colleagues for relationships of a given number of patients shared than respondents in the highest tertile of number of connections (Figure SA3).

To better understand how the network of ties sampled and measured in our survey compared with the larger network of ties present in our Medicare database, we plotted two illustrative networks in Figure 3. We first visualized the relationships among the sampled physician population (including nonrespondents) in our sample based on all of the ties corresponding to six or more patients shared (based on the claims data) that were presented to respondents in the survey (Figure 3A). The network of these ties is what we could have measured for our sample if we did not have access to administrative data. Next, we plotted the network of relationships based on our entire Medicare database for all of the sampled physicians and their ties to other physicians outside of the physicians' organization, again only including ties of six or more patients shared. This much broader network reflects the scale of information that is available to map networks with administrative data (Figure 3B). This also demonstrates how these methods could be used to capture network data for all physicians in a geographic area.

## DISCUSSION

We conducted a survey examining professional relationships among physicians in an academic physicians' organization and compared physician responses with information gleaned from Medicare data for over 46,000 patients treated by those providers. The response rate for our study was 63 percent, a relatively high response rate for a survey of physicians (Asch, Jedrziewski, and Christakis 1997), especially in the case of seeking network ties (Iyengar, Van den Bulte, and Valente 2010). Our results support the hypothesis that patient-sharing, as measured using administrative data, is a valid method for

Figure 3: Physician Networks Constructed from Survey-Based and Claims-Based Relationships




This figure depicts two different plots of the largest connected network of physicians in the survey sample and their relationships. For visual clarity, only ties with a strength of six patients shared or higher are shown in both (A) and (B), which excludes some of the physicians and relationships. (A) depicts the relationships among the sampled physician population (including nonrespondents) as measured by the relationships presented in the survey (no more than 20 per respondent), with ties recognized in the survey labeled as blue lines and ties measured by Medicare claims, but not recognized by a respondent shown in gray. (B) shows the same set of respondents and nonrespondents, with the addition that all ties and other physician relationships measured by administrative claims are displayed, with the ties confirmed by survey measurement (by design a small subset of total sample of ties) highlighted in blue.

identifying relationships between physicians. We observed that the probability of a physician respondent reporting a relationship with another physician increases as these two physicians share more patients, up to a plateau of approximately 9–10 patients. These results are clinically intuitive, since one would expect two physicians to be more likely to be information-sharing colleagues if they share a significant number of patients.

In addition, we observed a contrast between the number of relationships recognized by respondents depending on their specialty. Overall, PCPs recognized more relationships than either surgical or medical specialists, with an even more pronounced difference in probabilities for relationships with fewer patients shared. This finding supports the concept of a PCP's role

in care coordination: since PCP's are often the providers who are actively managing and maintaining specialist relationships (Starfield, Shi, and Macinko 2005), they would probably be more likely to recognize the specialists whom their patients see.

The results of this study also help inform the critical issue of how to set a threshold for defining a physician relationship when using patient sharing from administrative data as a diagnostic test for the presence of a relationship. We found that there was no clinically significant difference in the proportion of relationships recognized within an academic medical center when physicians share zero patients or one patient during the course of year, corresponding to 18 percent and 19 percent relationships recognized by respondents, respectively. Therefore, very low-volume ties between physicians are likely to emerge by chance and, in the setting of the population of this study, carry little extra information about the relationship between two physicians. Therefore, those interested in studying referral or information-sharing relationships between physicians could safely exclude ties with one patient shared over a year. As the threshold for defining a relationship is set higher, as shown in Figure 2, a researcher will be balancing the competing priorities of enriching the sample for true positive ties while not inducing too many false-negative ties (i.e., removing real, but weaker, ties). Of course, a threshold based on a *relative* number of patients shared may be more appropriate than a threshold based on the *absolute* number in other settings; for example, the sharing of two patients between a PCP and a neurosurgeon could be more meaningful than the same number of patients shared between a PCP and a cardiologist. In addition, the specialties of the two physicians likely play a very important role in choosing the most appropriate threshold for inferring a relationship between physicians. The previous example of the relationship between a PCP and a neurosurgeon also illustrates this principle. This study was not powered to evaluate the appropriate threshold between physicians of different specialties, though this would be a logical next step for future study. One possible avenue to explore could be to expand on the idea of variable thresholds already being explored in the network science literature (Serrano, Boguna, and Vespignani 2009).

The results of this study demonstrate several advantages to the use of administrative data over de novo surveys to identify the connections among entire networks of doctors. First, networks of thousands of doctors can be identified and mapped at relatively low cost based on the identification of all pairs of doctors who share patients (above some threshold). Figure 1 suggests that the strength of a connection between physicians might be inferred by the

total number of patients any two doctors share, thus allowing researchers to generate networks weighted by relationship strength in a way that would be challenging to measure by survey. Finally, and perhaps most important, the use of administrative data to identify networks offers the promise of vastly less missing data, since virtually all doctors who file claims or report encounter data will be in the network (not just those who respond to surveys) and virtually all ties can be ascertained (not just the limited number that can be elicited from the respondent within the constraints of a survey). This advantage is especially clear with the visual aid of plotting the networks created by the relationships of the physicians we studied. In Figure 3A, the network that we can ascertain between the respondents in our sample at first glance looks fairly detailed. But the limitations of using only survey data to map networks is more clear when comparing Figure 3A to the full network we can plot with administrative data in Figure 3B.

This study is subject to several limitations. First, our survey is susceptible to nonresponse bias, despite our relatively high response rate. Respondents and nonrespondents differed significantly in some of the characteristics we measured. Also, our study population was limited to physicians within a single academic physicians' organization, most of whom were based in a large, Boston-area academic medical center. Therefore, caution should be used in generalizing these results to any group of physicians in the United States.

Another issue is that, for the roster section of this survey conducted in 2010, we only asked respondents about relationships observed in Medicare data during 2006. We attempted to compensate for this issue in two ways: first, we included in the roster "negative" ties where the respondent and cited physician did *not* share patients in our database, but were part of the same physicians' organization. Second, before presenting respondents with the names of physicians in a roster, we asked respondents to generate the names of up to two physicians in three specialties of their choice to obtain a less biased selection of the our respondent's relationships with other physicians. We found that we could find a patient-sharing relationship in 2006 for 69 percent of the 1,269 relationships where we could clearly identify the named physician. We were thus able to match a sizable majority of the named relationships; nevertheless, we potentially missed up to 31 percent of relationships that exist, but that we were unable to observe. Many relationships that we missed may be current relationships that were not present in 2006, 4 years before we collected the survey data; in addition, Medicare data unavoidably represents only a subset of patients seen by the respondents.

In conclusion, we conducted a novel examination of the ability of patient sharing to predict physician relationships. We found that the probability of physicians recognizing another physician as a colleague increases strongly as more patients are shared, particularly with more than one patient. In addition, there are differences in the proportion of relationships recognized by respondents depending on their specialty, with PCPs overall being the most likely to recognize a relationship with another physician. This work has significant implications for future research into physician referral patterns and information sharing by validating the use of abundant administrative data to examine physician networks.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Appendix SA1: Author Matrix.

Table SA1: Diagnostic Values for Using Shared Patients to Asses Physician Relationships.

Figure SA1: Distribution of Number of Connections to Other Physicians in the Sample of Eligible Respondents.

Figure SA2: Distribution of Strength of Physician Patient-Sharing Ties in the Sample of Eligible Respondents.

Figure SA3: Probability that Respondents Identified a Relationship to a Listed Physician by Number of Patients Shared.

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