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Title page

Manuscript Title: Analysis of the Patient-sharing Network in Hypertension Management: A Retrospective Study in China

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Analysis of the Patient-sharing Network in Hypertension Management: A Retrospective Study in China

Abstract

Objective

To explore the robustness of the patient-sharing network method and validate possible influencing factors in China.

Design, setting and participants

We conducted a patient-sharing network analysis to describe the persistence of patient-sharing relationships and logistic regression to analyze factors influencing the persistence of patient-sharing relationships in the Yinzhou Health Information System (YHIS) from January 1, 2010, to December 31, 2018, all outpatient records that had a hypertension diagnosis were included in this study.

Outcome measures

The persistence ratio was defined as the proportion of the patient-sharing relationships in a given year that continued to exist in the following year, the one-, two-, and three-year persistence to test the robustness of the findings.

Results

This study included 3,916 physicians from 42 public healthcare facilities in Yinzhou. The one-year persistence ratio fluctuated around 80% and the three-year persistence ratio was around 60% over the study period. The strength of the relationship, tie characteristics, and physician specialty were important factors influencing the persistence of the relationships. The persistence of the relationships increased significantly as the strength of the relationships increased (for relationships with strength $\in$ [3, 5), OR = 3.987, 95% CI: 3.896-4.08; for relationships with strength $\in$ [5, 7), OR=6.379, 95% CI: 6.147-6.626; and for

relationships with strength ∈ [7, 9), OR=8.373, 95% CI: 7.941-8.829). Physicians from the same healthcare institution were more likely to form ties that persisted for at least one year compared with physicians from different institutions (OR=1.510, 95% CI: 1.480-1.540).

Conclusions

Our study showed that physicians frequently formed relationships with other physicians through sharing patients in Yinzhou, China, and these relationships had similar rates of persistence to studies conducted in developed countries, which indicated that findings of social networks analyses conducted in developed countries still hold value in developing countries.

Strengths and limitations of this study

- The first study that depicted the structure of patient sharing network in hypertension management in China
- Over 80% of physician relationships formed through sharing patients persisted over one year in China
- The strength of the relationship, tie characteristics, and physician specialty were important factors influencing the persistence of relationships
- The analysis was limited to a specific area of China
- The detailed characteristics of physician were not included in the analysis since the unavailability of data

Keywords

Social networks; Patient-sharing relationships; Knowledge diffusion; Persistence ratio; Influencing factors

Funding statement

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Availability of data and materials

The datasets used and/or analysed in the current study are available from the corresponding author on reasonable request.

Introduction

The translation and diffusion of knowledge inevitably affect physicians' prescribing behaviors, especially among physicians providing care to shared patients, with implications for patient health and healthcare utilization 1. An increasing number of research has utilized social network as a tool to understand patient-sharing relationships of healthcare professionals 2, 3. Such analyses can deepen understandings of the influences of knowledge exchange, either formal or informal, on the clinical practice of healthcare providers and identify pathways to improved quality of care and efficient use of healthcare resources 4, 5.

Previous studies have explored the impact of social networks on the prevention and control of infectious diseases, including tuberculosis and malaria, and on knowledge diffusion in managing non-communicable diseases (NCDs) such as diabetes and hypertension 3, 6-9. Patient-sharing networks among physicians signal formal and informal exchange of knowledge and information while providing care and can help identify and understand problems in medication adherence and therapeutic inertia, both of which are essential to managing NCDs 10-17. Published studies exploring patient-sharing networks were mainly from developed countries, which found that network-based interventions are effective methods to reduce healthcare costs and improve the quality of healthcare services 18-22. In the US, a cross-sectional study found that more dispersed patient care might contribute to fragmentation of care and increased costs 18. Further, studies have found that physician network connections in the management of diabetes, Parkinson's disease, and acquired immunodeficiency syndrome, could help to improve clinical outcomes and quality of care of patients because professional networks are important for disseminating new medical information among physicians 20-22. The persistence (also known as stability) and strength of the patient-sharing relationships are important metrics in network analyses 23-25. Long-term patient-sharing relationships could enable physicians to foster trusting relationship with one another and help to create new referral loops and are thus facilitative to coordinating care and reducing costs 23, 26. Studies have found that many factors might affect the persistence ratio of patient-sharing relationships, including tie characteristics,

physician specialty, strength, and when such relationships occurred 18, 24, 27, 28. However, patient-sharing relationships and the effect they can exert on provider practices can vary across regions with differently structured healthcare systems. It is uncertain if examining these relationships could be a viable tool in studying health services in developing countries and how these relationships can vary from developed countries and regions 24, 29-31.

Few studies in low- and middle-income countries have utilized network analysis to understand professional communication among healthcare providers. Before developing network-based interventions, we need to first understand the structure and persistence of physicians' patient-sharing networks in developing countries and identify influencing factors and their mechanism of action 32. In China, hypertension is an NCD with a high prevalence of 44.7% among adults aged 35-75 years but is generally poorly managed and requires further care enhancements. Only 30.1% of those diagnosed with hypertension were on antihypertensive medicines, of whom lower than 6% had their symptoms properly managed 33-36. Global study has found that increased density of qualified general practitioners played an important role in hypertension management; in India, a previous study found that access to healthcare is closely tied to hypertension management; in Sweden, a cohort study found that education and feedback strategies could help to refine the clinical guideline of hypertension management; while in China, the number of primary care physicians who are formally licensed, the emphasis on medical education, primary care coordination, and continuity are also important factors for the hypertension management 37-40. This evidence could help to identify the importance of physicians in hypertension management, but there are lack of related studies to further analyze the knowledge diffusion among physicians in hypertension management in China. Therefore, we conducted a social network analysis to describe the persistence of patient-sharing relationships of physicians managing patients with hypertension and identify factors influencing the network in China.

Methods

Study Design

In line with previous studies, the patient-sharing relationship between physicians (i.e., two or more physicians providing care to the same patients) was recorded in and identified through reviewing records of outpatient visits, with the number of the shared patients between physicians representing the strength of the relationship 24. Patient-sharing represents exchanges of knowledge among physicians and could therefore be used to assess physicians' coordination, a clear target for cost-saving and improving the quality of medical care 41, 42. To understand the network structure and factors influencing patient-sharing relationships in Yinzhou district of Ningbo, a coastal city in south-east China, we built a theoretical model of Chinese physicians' professional network based on patient-sharing relationships.

Data Sources

We extracted data from the Yinzhou Health Information System (YHIS), which was established by the local health department in 2005. The system collects and manages electronic medical records of people residing in Yinzhou district and covered data including general characteristics, prescription, outpatient visit records. All information stored in the system has been de-identified to safeguard patient privacy. In 2018, Yinzhou district is home to about 1.34 million residents 43, 44.

Study Population

We extracted all outpatient records from YHIS. Inclusion criteria were: (1) the patient was diagnosed with hypertension, shown by the corresponding ICD-10 codes (I10, I11, I12, I13, and I15); (2) the patient's hypertension diagnosis was between January 1, 2010, to December 31, 2018; and (3) Primary Care Physicians (PCPs) or specialists working in secondary and tertiary hospitals who treated adult hypertension patients (≥18 years old). Our exclusion criteria were: (1) outpatient records generated from patients not residing in Yinzhou

district; and (2) patient-sharing relationships not occurring in the same year (e.g., a physician provided care to this patient in year 1 while the other physician only provided care to this patient in year 2). There is a total of 27,267 hypertensive patients and 3,916 physicians included in this study 30.

Outcome Measures

The threshold was defined as the minimum strength of patient-sharing relationships needed to form a physician network. For instance, "threshold = 2" indicated that two physicians would need to share at least two patients to be regarded as in a network. The threshold could help to identify stable patient-sharing relationships and reduce the impact of incidental connections that have a lower probability of knowledge exchange 30. The persistence ratio was defined as the proportion of the patient-sharing relationships in a given year that continued to exist in the following year. If ten pairs of patient-sharing relationships were observed in 2008 and eight of them persisted to 2009, the one-year persistence ratio would be 80%, as shown in Figure 1. Connections that persisted for two or more years were seen as long-term relationships that could diffuse knowledge more intensely and thus have a larger effect on prescribing behaviors of the physicians involved 29.

Many factors might affect the persistence ratio of patient-sharing relationships, including tie characteristics, physician specialty, strength of the relationship, and when such relationships occurred 29. Tie characteristic was a binary variable reflecting whether the patient-sharing relationship happened within one or across multiple hospitals. A patient-sharing relationship was also classified according to specialties involved and assigned to a category of the followings: “PCPs- PCPs”, “PCPs-Specialists”, and “Specialists-Specialists”. The year when patient-sharing relationship occurred was defined as the year when the outpatient visit (signaling a patient-sharing relationship) happened. Based on previous literature, we assumed that the knowledge translation and diffusion across years and hospitals could promote coordination of PCPs and specialists and subsequently improve healthcare system efficiency 27. Variable selection and definition are reported in Table 1.

Statistical Analysis

We conducted logistic regression to analyze factors influencing the persistence of patient-sharing relationships, with the 95% confidence interval (CI) and P-value reported for each odds ratio (OR) 45. Strength ∈ [1 , 3), " Tie characteristics " = "no", " Physician specialty " = " PCP - PCP", and the year of 2010 were set as reference group. To visualize the structure of the patient-sharing network, we chose the Fruchterman-Reingold algorithm, a spring-embedder method, to present the physician network, with two physicians having stronger patient-sharing relationship lying closer in the illustration 36, 46. In the analysis of the persistence ratio of patient-sharing relationships, we conducted a sensitivity analysis based on thresholds and years of persistence of patient-sharing relationships; in the analysis of the influencing factors of patient-sharing relationships, we conducted sensitivity analyses on the one-, two-, and three-year persistence to test the robustness of the findings. All analyses were performed using R 4.0.4, a two-sided P value < 0.05 was considered statistically significant.

Results

Our final sample included 27,267 hypertensive patients and 3,916 physicians from 42 public healthcare facilities. The number of patients, physicians, and public healthcare facilities each year are described in Table 2. There were 1,264 physicians included in 2010 according to the inclusion criteria, including 980 (77.5%) PCPs and 284 (22.5%) specialists. The number of physicians remained relatively stable from 2011 to 2018.

Structure of patient-sharing network

The patient-sharing network is visualized in eFigure. When threshold equaled 1, relationships seemed random and displayed trends vastly different from those shown when other thresholds were applied. Changes in the persistence of patient-sharing relationships are shown in Figure 2. When threshold was set at 3 (i.e., only patient-sharing relationships with strength⩾3 were retained), the physician network demonstrated a gradually downward trend

as compared with when threshold was set at 1. Patient-sharing relationships showed similar patterns when the threshold was set at 3, 5, 7, or 9, with at least 80% of the relationships persisting after one year (Threshold=3: 81.8%, Threshold=5: 85.8%, Threshold=7: 86.9%, and Threshold=9: 87.4%) and at least 60% of the relationships persisting after three years (Threshold=3: 60.4%, Threshold=5: 64.4%, Threshold=7: 66.1%, and Threshold=9: 66.5%).

Persistence of patient-sharing network

The number of patient-sharing relationships (i.e., physician ties) in 2010 was 36,543 while the number of relationships per physician was 28.9. Among these ties, 67.3% happened between physicians from different health care institutions (HCIs) while others were between physicians from the same HCI. The majority (60.9%) of observed connections were between PCPs, 30.9% were between PCPs and specialists, and 8.2% were between specialists. Many (68.1%) observed connections had a strength $\in [1, 3)$ (i.e., the two physicians had one or two tie(s)), only 11.2%, 5.3%, and 2.9% had a strength $\in [3, 5)$ (i.e., the two physicians had 3 or 4 ties), strength $\in [5, 7)$, and strength $\in [7, 9)$. There are many patient-sharing relationships had a strength $\geqslant 9$ (11.2%), which might indicate that there exist many stable patient-sharing relationships across years. Both the number of patient-sharing relationships and the persistence of these ties showed upward trends, as shown in Table 3.

Factors influencing the persistence of patient-sharing network

Results of the logistic analysis of the factors influencing the persistence of patient-sharing relationships are shown in Table 4. The persistence of the relationships increased significantly as the strength of the relationships increased. Compared with the relationships that had a strength $\in [1, 3)$, OR was 3.987 (95% CI: 3.896-4.08) for relationships with a strength $\in [3, 5)$ was 3.987 (95% CI: 3.896-4.08), 6.379 (95% CI: 6.147-6.626) for relationships with strength $\in [5, 7)$, and 8.373 (95% CI: 7.941-8.829) for relationships with strength $\in [7, 9)$. Physicians from the same HCI were more likely to form connections that persisted at least one year compared

with physicians from different HCIs (OR=1.510, 95% CI: 1.480-1.540). PCP-Specialist relationships and Specialist-Specialist relationships had lower rates of one-year persistence compared with the PCP-PCP relationships (OR<1, p<0.001).

Sensitivity analysis of patient-sharing networks

We conducted a sensitivity analysis using two-year and three-year ties. Results of the sensitivity analysis confirmed that the strength of the relationship, tie characteristics, and physician specialty were important factors influencing the persistence of physician's patient-sharing relationships. (Table 4)

Discussion

This study provides insights into how frequently physicians in China fostered relationships with each other through delivering care to a shared patient and how strong and persistent these relationships were. We found that over 80% of physician relationships formed through sharing patients persisted over a year and 60% of these relationships persisted over three years, a result comparable to results from developed countries 29. The strength of the relationship, tie characteristics, and physician specialty were important factors influencing the persistence of the physician's patient-sharing relationships. To our knowledge, this study is the first to describe the structure and influencing factors of the patient-sharing network among physicians engaged in the management of NCDs in a developing country. These findings suggest that physicians' patient-sharing networks can serve as a stable and viable target for future studies or interventions to promote care coordination and knowledge diffusion in China.

Physicians with more shared patients may form a more stable patient-sharing relationship and therefore enjoy a higher persistence ratio and exert stronger influence on knowledge diffusion within the network 24. Previous studies found that knowledge diffusion could strengthen the quality and coordination of healthcare services, as seen in lower rates of emergency room visits and lower medical costs in patients treated by physicians with ties

of stronger persistence 29, 47. Physicians with a larger number of and more persistent relationships were also more likely to experience knowledge diffusion that helped to strengthen collaborations among physicians, even those formed among physicians of different hospitals, to produce desirable patient outcomes such as lowered odds of 30-day readmissions, adverse events, and so forth 48-51.

In middle-income countries like China, the burden of cardiovascular diseases were more inequitably distributed than high-income countries, which is often exacerbated by a severe under-resource of personnel with expertise in and infrastructure supporting the management of cardiovascular diseases 16. Developing interventions that utilize patient-sharing networks already present in physicians' day-to-day practices and that strengthen the hierarchical medical system can be an effective and cost-saving approach to influence physicians' behaviors, improve their coordination, and promote patient outcomes. As patient-sharing relationships formed among physicians of different HCIs can diffuse knowledge and influence their prescribing behavior, they can be utilized to promote the optimization of patient treatment plans to reduce patient burden and improve clinical outcomes in managing NCDs like hypertension 13, 18, 47.

Our study confirmed that physicians from geographically proximate hospitals were more likely to form patient-sharing relationships, a result similar to a previous study 52. These relationships among physicians across different HCIs and specialties could lend insight into the barriers and promoters of an efficient healthcare system 53. They are conducive to the knowledge diffusion beyond one single HCI, which has the potential to spread clinical treatment experience to improve quality of care in primary health care facilities, where physicians normally have less clinical capacity 18. This is supported by a previous study which found that high value of network statistics, reflecting global connectivity, is beneficial to medical cost savings 31. In contrast, hospitals with greater dispersion were associated with greater rates of readmission and lower rates of emergency department throughput 31, 54. Patient-sharing relationships among physicians can be a clear target to develop network-based interventions to curb these unfavorable outcomes.

The Chinese government has launched a hierarchical medical system policy in 2014, aiming to alter patients' healthcare-seeking behaviors. After its implementation, most patients are expected to first visit primary care facility, which ideally should be the same facility to ensure consistency in care. This redirection of patient flow to primary care facilities may cause PCPs to share patients more frequently, and thus more physicians could have more possibility to form more strength patient-sharing relationships 55. We also found that the proportion of patient-sharing relationships formed between physicians practicing at the same HCI was lower than that reported in developed countries 46, 56, 57. This may imply that HCIs in China have not established a harmonized patient referral system and thus patients frequently move between HCIs when certain needs remained unmet, which helped to form physician connections across HCIs 58. A previous study has found that PCPs has a central role in managing chronic diseases and a hierarchical medical system can leverage the management of NCDs 42. Our study observed significant fluctuations in the persistence ratio of patient-sharing relationships in 2015 when the hierarchical medical system policy was implemented in China, which may reflect the impact of policy on physician's patient-sharing relationships.

There are several limitations to this study. First, we established the social network of physicians in Yinzhou, China by identifying patient-sharing relationships, however, we were unable to observe the actual patient flow and the dynamics of these relationships from the retrospective data. A fuller landscape of the impact of knowledge diffusion through these relationships on physicians' prescribing behaviors may only be gained through conducting qualitative studies in the future. Second, we limited the disease area to hypertension to represent the characteristics of the patient-sharing network of physicians managing NCDs. However, physician networks may be affected by differences in chronic diseases, such as patient characteristics. Third, due to data limitations, our study did not specify the specialties involved or analyze physician characteristics that may affect their patient-sharing relationships, and the actual meaning of some important factors could not be clearly illustrated, nonetheless, this is a valid research question that awaits further explorations.

Conclusions

We found that physicians frequently formed relationships with other physicians through sharing patients in Yinzhou, China. These relationships showed similar rates of persistence to studies conducted in developed countries, where network-based interventions have been proven effective in curbing some problems in healthcare delivery and patient outcomes. Future research and interventions to promote care coordination and knowledge diffusion can leverage these naturally occurring relationships and seek to understand mechanisms through which they can exert influences on healthcare providers' practices and coordination with one another.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Peking University Medical Ethics Committee (IRB00001052–22052). Written informed consent for participation was not required for this study according to the national legislation and the institutional requirements.

Authors' contributions

Zhiwen Gong: Software, Formal analysis, Writing- Original draft preparation; **Ruilin Wang**: Software, Formal analysis, Writing- Original draft preparation; **Huajie Hu**: Data Curation, Software, Formal analysis, Writing- Original draft preparation; **Tao Huang**: Data Curation, Validation, Writing - Review & Editing; **Huangqianyu Li**: Writing - Review & Editing; **Sheng Han**: Conceptualization, Supervision, Writing - Review & Editing; **Luwen Shi**: Conceptualization, Supervision, Writing - Review & Editing; **Xiaodong Guan**: Conceptualization, Supervision, Writing - Review & Editing, Funding acquisition.

All authors gave final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately.

Conflicts of Interest

The authors declare that they have no competing interests.

Abbreviations

YHIS: Yinzhou Health Information System

NCDs: non-communicable diseases

PCPs: Primary Care Physicians

CI: confidence interval

OR: odds ratio

HCIs: Health Care Institutions

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Table 1. Variable selection and definition in the analysis of patient-sharing relationship in Yinzhou

Variable	Definition	Meaning
Persistence ratio	The proportion of the patient-sharing relationships in a given year that continue to exist in the following year.	Reflecting long-term relationships across years, and the professional knowledge may diffuse through the network and have an effect on the physicians' prescription behavior.
Relationship strength	The number of the sharing patients between physicians.	Representing a more stable patient-sharing relationship, higher persistence ratio and long-term patient-sharing relationships have positive effects on knowledge diffusion in the network.
Hospital characteristics	Whether the related physicians of patient-sharing relationship from the same hospital.	The patient-sharing relationships among different physician specialties are conducive to the Representing whether knowledge diffusion in a larger geographical area, helpful to the update of clinical treatment experience.
Physician specialty	The specialty of the related physicians of patient-sharing relationship.	Regions with higher persistent ties tended to have lower rates of emergency medical visits, and regions where PCPs had more physician connections were more likely to have higher emergency medical visits.
Relationship occurrence year	The year of the visit when the physician-sharing relationship happened.	The impact of occurrence year on the patient-sharing relationships could help to understand the trend and other influencing factors on the patient-sharing relationships (e.g., policy factors etc.) could help to explore and assess the network-based interventions.

Table 2. Basic characteristics of physician network for medication therapy management of hypertensive patients in Yinzhou from 2010 to 2017

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Number of patients									
	77063	97187	110507	119920	129021	135955	150239	181997	137582
Number of hospitals									
Primary care facilities	22	23	25	25	25	25	26	33	26
Secondary hospitals	1	1	1	1	1	1	2	3	2
Tertiary hospitals	2	2	2	2	3	3	3	5	5
Total	25	26	28	28	29	29	31	41	33
Number of physicians									
Primary care facilities	980	1024	1084	1072	1070	1089	1060	1287	948
Secondary hospitals	54	59	68	77	62	90	153	145	88
Tertiary hospitals	230	301	323	365	440	500	685	674	703

Table 3. Characteristics of patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2017

				2010	2011	2012	2013	2014	2015	2016	2017	2018
Number of observed connections				36543	55934	61509	66206	67203	74541	79029	89463	68610
Not in same hospital				24587	39022	43211	46304	47896	53834	55977	64089	50851
In same hospital				11956	16912	18298	19902	19307	20707	23052	25374	17759
Physician specialty	PCP	-	PCP	22272	30816	35422	37182	38386	38403	37818	47477	36571
	PCP	-	Specialist	11285	19599	20703	22490	22877	28384	29807	30093	23805
	Specialist	-	Specialist	2986	5519	5384	6534	5940	7754	11404	11893	8234
Strength			[1,3)	24871	38008	41785	45376	46330	52130	57503	67378	51649
			[3,5)	4101	6398	6953	7324	7073	7988	7470	8484	6594
			[5,7)	1937	2904	3028	3284	3176	3234	3099	3292	2481
			[7,9)	1054	1652	1826	1883	1830	2002	1795	1817	1370
			≥9	4580	6972	7917	8339	8794	9187	9162	8492	6516

(Note) PCP: Primary Care Physicians.

Table 4. Logistic regression of persistent ties for patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2017

	One-year persistent ties			Two-year persistent ties			Three-year persistent ties		
	OR	95% CI		OR	95% CI		OR	95% CI	
Strength									
[1,3)	-								
[3,5)	3.987 ***	(3.896 , 4.080)		3.203 ***	(3.130 , 3.274)		2.790 ***	(2.724 , 2.858)	
[5,7)	6.379 ***	(6.147 , 6.626)		4.716 ***	(4.563 , 4.874)		3.796 ***	(3.669 , 3.924)	
[7,9)	8.373 ***	(7.941 , 8.829)		6.019 ***	(5.755 , 6.290)		4.614 ***	(4.424 , 4.816)	
≥9	11.965 ***	(11.600 , 12.354)		8.290 ***	(8.077 , 8.508)		6.784 ***	(6.032 , 6.341)	
Hospital characteristics									
Not in the same hospital	-								
Same hospital	1.510 ***	(1.480 , 1.540)		1.402 ***	(1.373 , 1.430)		1.358 ***	(1.330 , 1.385)	
Physician specialty									
PCP - PCP	-								
PCP - Specialist	0.876 ***	(0.862 , 0.891)		0.693 ***	(0.680 , 0.705)		0.555 ***	(0.544 , 0.567)	
Specialist - Specialist	0.566 ***	(0.550 , 0.582)		0.463 ***	(0.450 , 0.476)		0.384 ***	(0.373 , 0.396)	
Year									
2010	-								
2011	0.803 ***	(0.779 , 0.826)		0.854 ***	(0.829 , 0.879)		0.937 ***	(0.909 , 0.965)	
2012	0.826 ***	(0.803 , 0.850)		0.914 ***	(0.888 , 0.940)		1.035 ***	(1.005 , 1.065)	
2013	0.791 ***	(0.768 , 0.813)		0.905 ***	(0.880 , 0.931)		0.696 ***	(0.676 , 0.716)	
2014	0.811 ***	(0.789 , 0.834)		0.599 ***	(0.583 , 0.617)		0.429 ***	(0.416 , 0.442)	
2015	0.510 ***	(0.496 , 0.524)		0.379 ***	(0.368 , 0.390)		0.221 ***	(0.214 , 0.228)	

(Note) PCP: Primary Care Physicians. Reference group: Strength ∈ [1 , 3), " Hospital characteristics " = "no", " Physician specialty " = " PCP - PCP", and the year of 2010. One-year persistent ties represent ties that generating in one year and persist in the next year, two-year represents persisting in next two years, and three-year represents persisting in next three years, when considering the three-year persistent ties, the ties generating in 2015 that persists in 2018, therefore the year of 2016, 2017, and 2018 were unobservable.

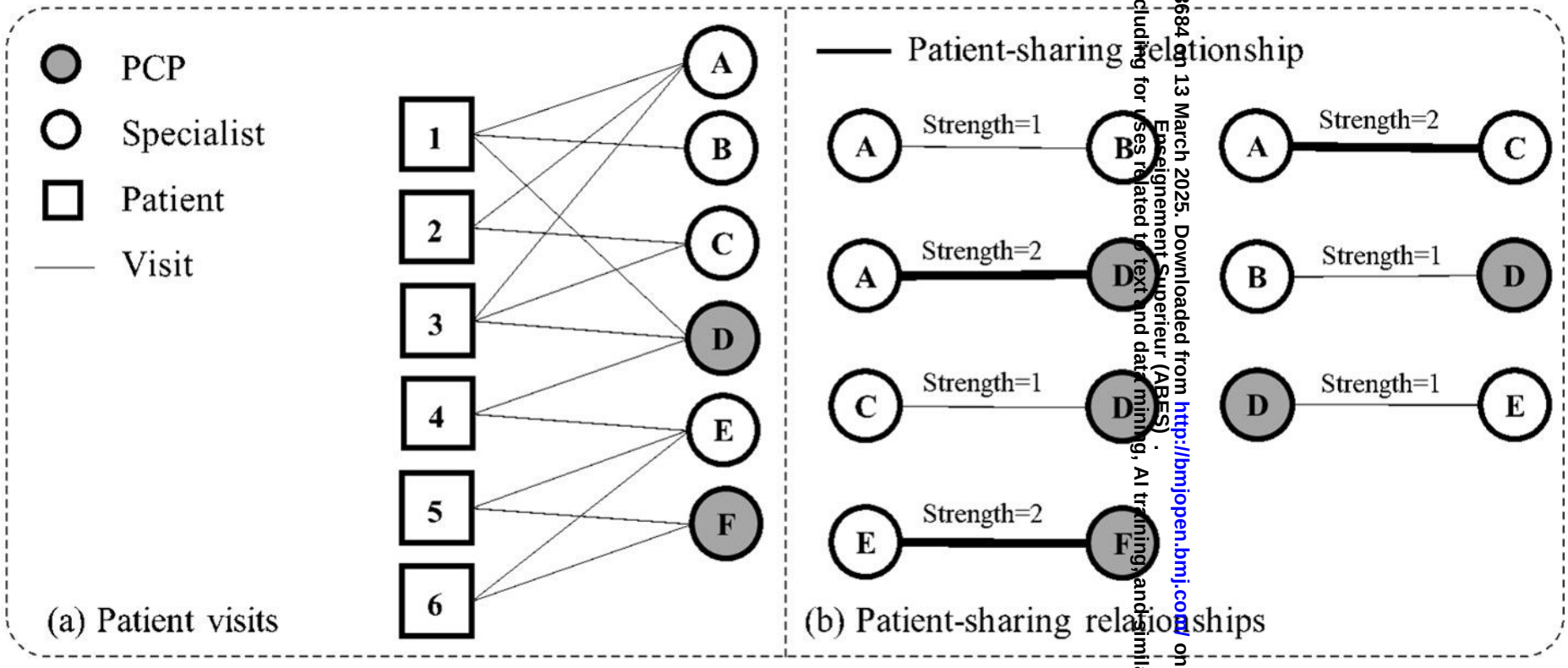


Figure 1 Schematic diagram of the patient-sharing relationships

Figure 1. Schematic diagram of the patient-sharing relationships

(Note) PCP: Primary Care Physicians. Node: physicians in the network; Tie: the connections between physicians in patients-sharing relationships; Strength: the weight of the ties between the two nodes, refers to the number in patients-sharing relationships.

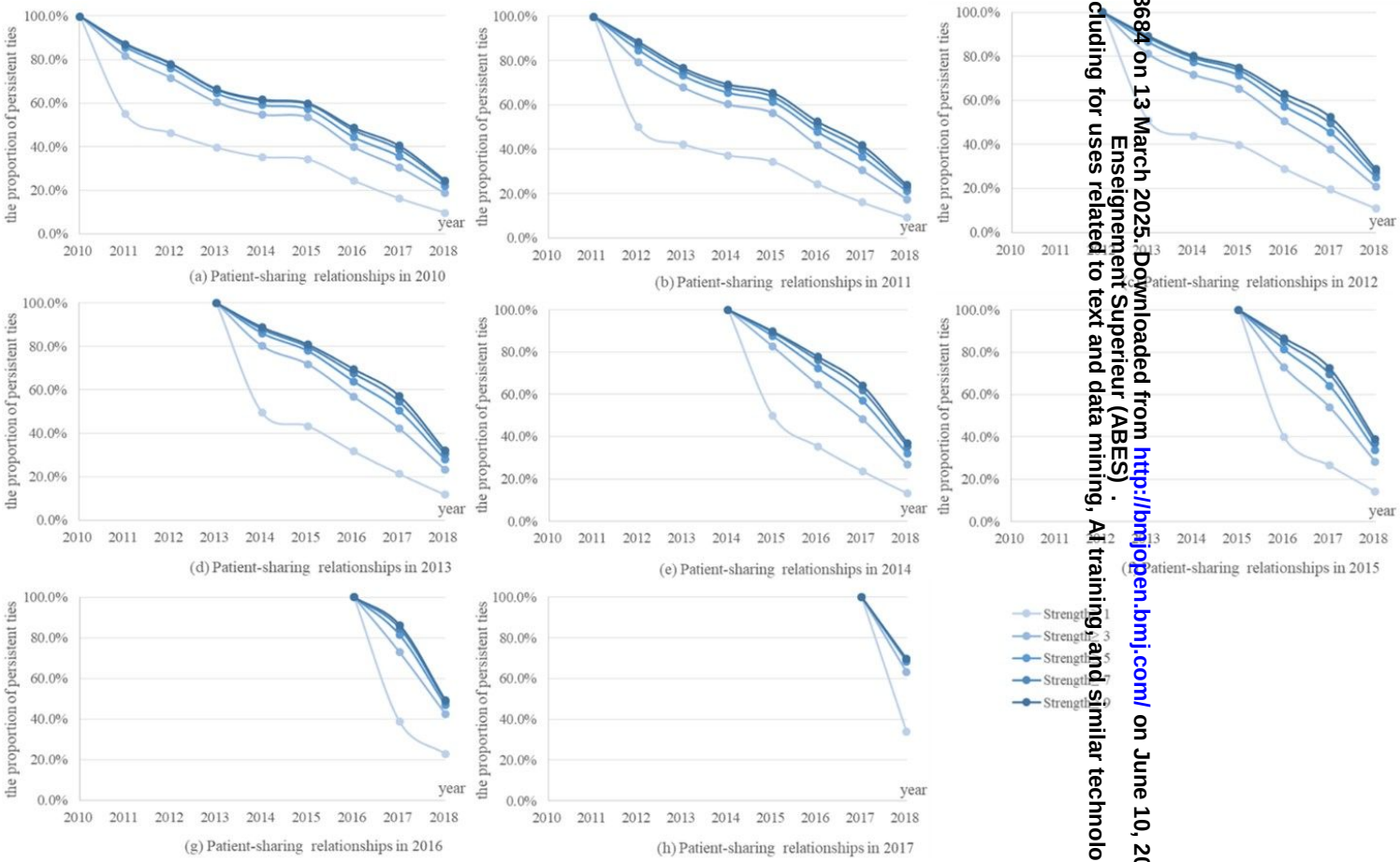
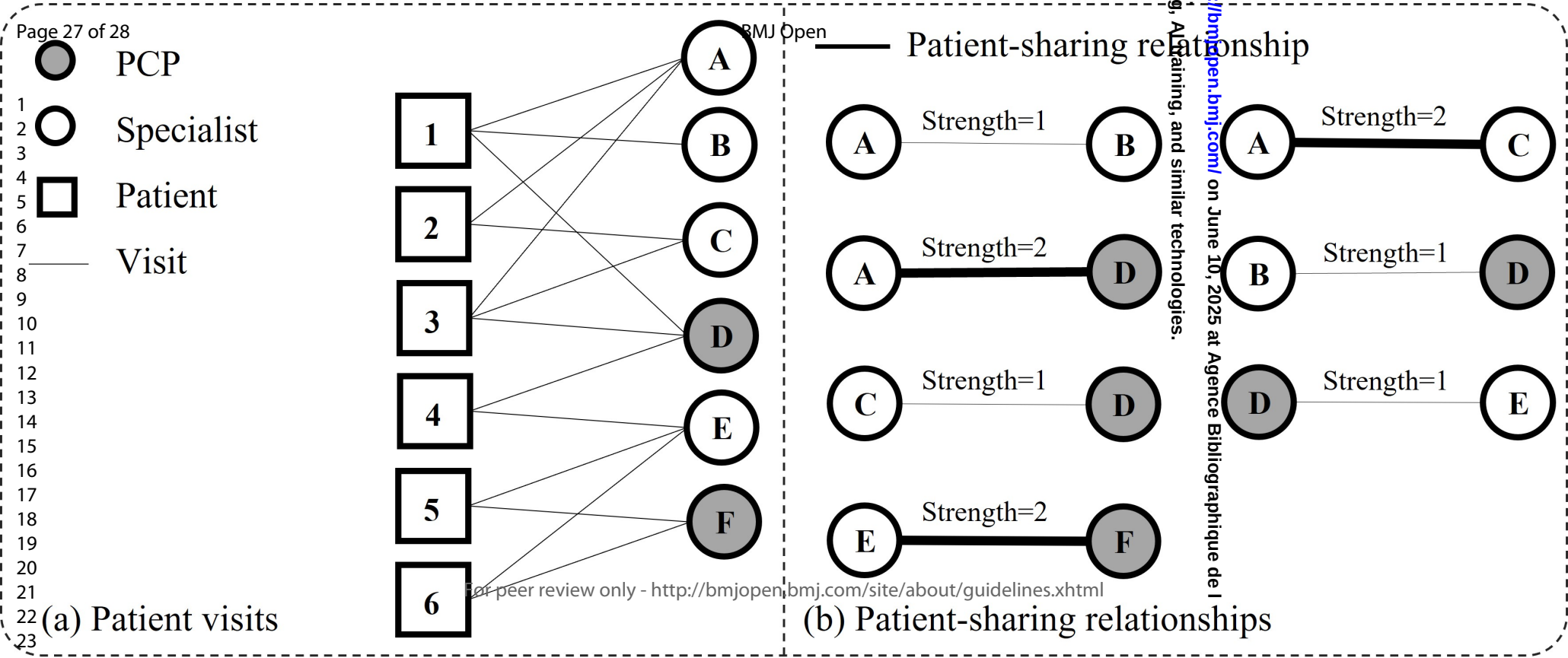
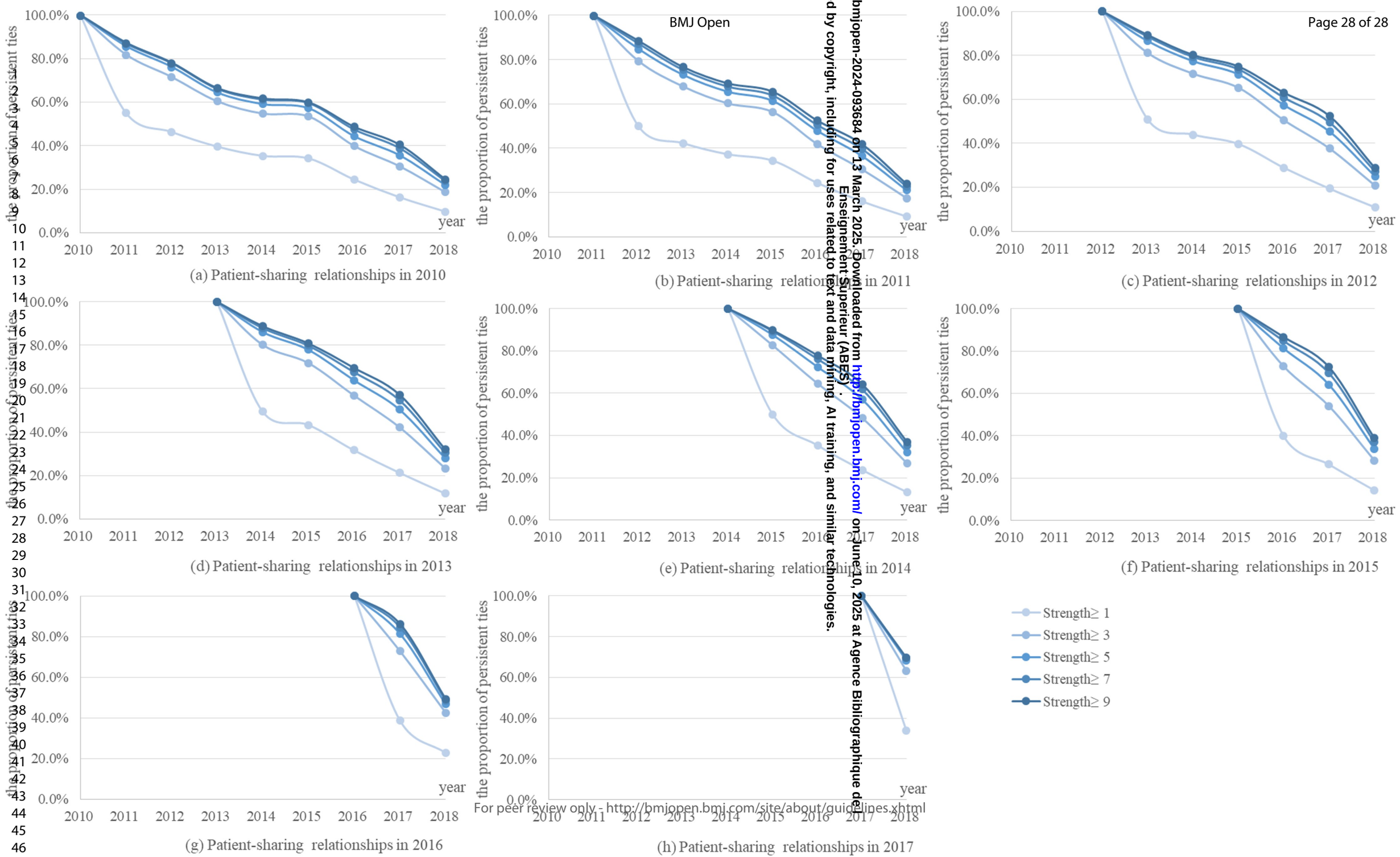


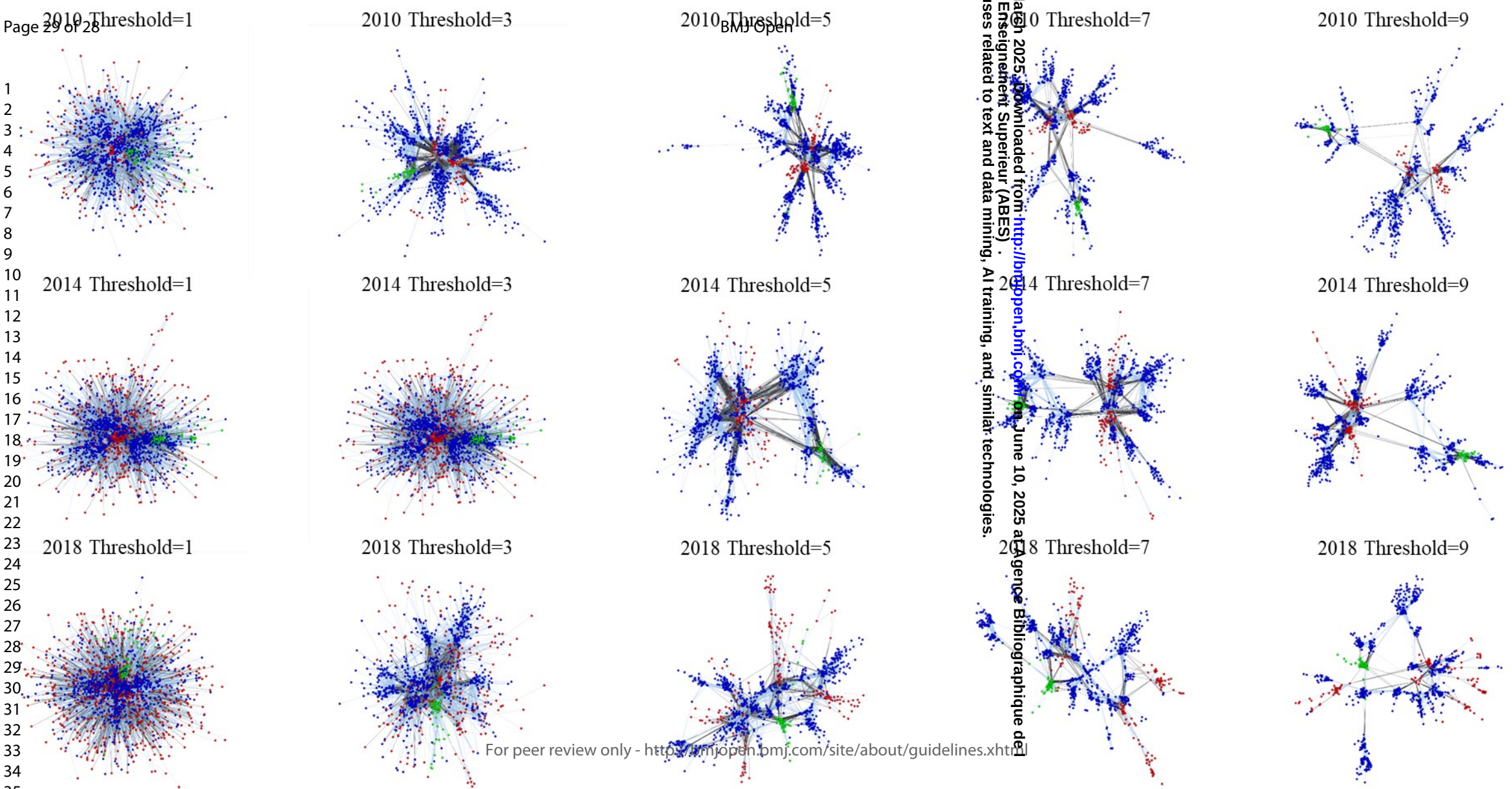
Figure 2 The proportion of persistent ties for patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2017

Figure 2. The proportion of persisitent ties for patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2017

(Note) Part (a) represents the proportion of persistent ties generating in 2010, and part (b)-(h) represent the proportion of persistent ties generating in 2011-2017, respectively.







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Title page

Manuscript Title: Analysis of the Patient-sharing Network in Hypertension Management: A Retrospective Study in China

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Analysis of the Patient-sharing Network in Hypertension Management: A Retrospective Study in China

Abstract

Objective

To explore the robustness of the patient-sharing network and validate the association between strength and persistence of physicians' relationship in China.

Design, setting and participants

We conducted a patient-sharing network analysis to describe the persistence of patient-sharing relationships and logistic regression to analyze factors associating with the persistence of patient-sharing relationships in the Yinzhou Health Information System (YHIS) from January 1, 2010, to December 31, 2018, all outpatient records that had a hypertension diagnosis were included in this study.

Outcome measures

The persistence ratio was defined as the proportion of the patient-sharing relationships in a given year that continued to exist in the following year, the one-, two-, and three-year persistence to test the robustness of the findings.

Results

This study included 3,916 physicians from 42 public healthcare facilities in Yinzhou. The one-year persistence ratio fluctuated around 80% and the three-year persistence ratio was around 60% over the study period. The strength of the relationship, tie characteristics, and physician specialty were important factors associating with the persistence of the relationships. The persistence of the relationships increased significantly as the strength of the relationships increased (for relationships with strength $\in$ [3, 5), OR = 3.987, 95% CI: 3.896-4.08; for relationships with strength $\in$ [5, 7), OR=6.379, 95% CI: 6.147-6.626; and for relationships with strength $\in$ [7, 9), OR=8.373, 95% CI: 7.941-8.829). Physicians from the same

healthcare institution were more likely to form ties that persisted for at least one year compared with physicians from different institutions (OR=1.510, 95% CI: 1.480-1.540).

Conclusions

Our study showed that physicians frequently formed relationships with other physicians through sharing patients in Yinzhou, China, and these relationships had similar rates of persistence to studies conducted in developed countries, which indicated that findings of social networks analyses conducted in developed countries still hold value in developing countries.

Strengths and limitations of this study

- We applied social network analysis methods to measure the structure and persistence of physician relationships in hypertension management.
- We used a well-established regional electronic health information system to capture comprehensive view of physician patient-sharing relationships across different level of healthcare institutions.
- The actual patient flow and dynamics of physician relationship were unable to observed.
- The association between the persistence of physician relationships and patient health outcomes were unable to be examined.
- The results were subjected to unmeasured confounding bias due to limited data availability.

Keywords

Social networks; Patient-sharing relationships; Knowledge diffusion; Persistence ratio; Influencing factors

Funding statement

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funder had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Data availability statement

Data may be obtained from a third party and are not publicly available. Data for the present study are property of Center for Disease Control and Prevention of Ningbo. The data are available from these authorities, but restrictions apply.

Introduction

The translation and diffusion of knowledge inevitably affect physicians' prescribing behaviors, especially among physicians providing care to shared patients, with implications for patient health and healthcare utilization.[1] An increasing number of research has utilized social network as a tool to understand patient-sharing relationships of healthcare professionals.[2, 3] Such analyses can deepen understandings of the influences of knowledge exchange, either formal or informal, on the clinical practice of healthcare providers and identify pathways to improved quality of care and efficient use of healthcare resources.[4, 5]

Previous studies have explored the impact of social networks on the prevention and control of infectious diseases, including tuberculosis and malaria, and on knowledge diffusion in managing non-communicable diseases (NCDs) such as diabetes and hypertension.[3, 6-9] Patient-sharing networks among physicians signal formal and informal exchange of knowledge and information while providing care and can help identify and understand problems in medication adherence and therapeutic inertia, both of which are essential to managing NCDs.[10-17] Published studies exploring patient-sharing networks were mainly from developed countries, which found that network-based interventions are effective methods to reduce healthcare costs and improve the quality of healthcare services.[18-22] These studies has reported that dispersed physician network connection contributed to fragmentation of care and increased costs,[18] while the intensive connections improved quality of care and clinical outcomes.[20-22] The persistence (also known as stability, referring to the continuation of relationships from the previous year into the next) and strength (the number of shared patients between two physicians) of the patient-sharing relationships have been identified as important metrics in network-based interventions.[23-25] Persistent patient-sharing relationships could enable physicians to foster trusting relationship with one another and help to create new referral loops and are thus facilitative to information exchange and coordinating care, which has been interpreted through theories of *diffusion of innovation* or *social contagion*.[23, 26, 27] Studies have found that many factors might affect the persistence ratio of patient-sharing relationships, including tie characteristics, physician specialty,

strength, and when such relationships occurred.[18, 24, 28] However, patient-sharing relationships and the effect they can exert on provider practices can vary across regions with differently structured healthcare systems. It is uncertain if examining these relationships could be a viable tool in studying health services in developing countries and how these relationships can vary from developed countries and regions.[24, 27, 29, 30]

Few studies in low- and middle-income countries have utilized network analysis to understand professional communication among healthcare providers. Before developing network-based interventions, we need to first understand the structure and persistence of physicians' patient-sharing networks in developing countries and identify influencing factors and their mechanism of action.[31] In China, hypertension is one of the most prevalent NCD, with a high prevalence of 44.7% among adults aged 35-75 years and generally poorly managed.[32] The management and control of hypertension typically requires collaborative across different healthcare institutional and healthcare providers, especially between various healthcare levels.[33, 34] Improved hypertension control have been reported in the well-connected physician professional environment,[35-38] underscoring the significant of promoting the physician's relationship in hypertension management. The patient-sharing network models were widely applied and validate methods to depict and measure these relationships among physicians in prior research.[39, 40] Given the knowledge gap in structure and persistence of physicians' relationships in China, we conducted a social network analysis to describe the persistence of patient-sharing relationships of physicians managing patients with hypertension and measure the association between strength and persistence of physicians' relationship in China, for providing insights for achieving better hypertension care coordination and disease control.

Methods

Study Design

In line with previous studies, the patient-sharing relationship between physicians (i.e., two or more physicians providing care to the same patients) was recorded in and identified through reviewing records of outpatient visits, with the number of the shared patients between physicians representing the strength of the relationship.[24] Patient-sharing represents exchanges of knowledge among physicians and could therefore be used to assess physicians' coordination, a clear target for cost-saving and improving the quality of medical care.[41, 42] To understand the network structure and factors associating with patient-sharing relationships in Yinzhou district of Ningbo, a coastal city in south-east China, we built a theoretical model of Chinese physicians' professional network based on patient-sharing relationships.

Data Sources

We extracted data from the Yinzhou Health Information System (YHIS), which was established by the local health department in 2005. Since its inception, the database has achieved registration of over 98% of permanent residents (approximately 1.3 million) and all healthcare providers (5.8 thousand) in Yinzhou.[43, 44] The system collects and manages electronic medical records of residents and covered data including general characteristics, prescription, outpatient visit records. All information stored in the system has been de-identified to safeguard patient privacy, thus the requirement of informed consent was exempted according to the national legislation and the institutional requirements. Ethical approval was obtained from the Peking University Institution Review Board (IRB00001052-22052).

Study Population

We extracted all outpatient records from YHIS. Inclusion criteria were: (1) the patient was diagnosed with hypertension, shown by the corresponding ICD-10 codes (I10, I11, I12, I13, and I15); (2) the patient's

hypertension diagnosis was between January 1, 2010, to December 31, 2018; and (3) Primary Care Physicians (PCPs) or specialists working in secondary and tertiary hospitals who treated adult hypertension patients (⩾18 years old). Our exclusion criteria were: (1) outpatient records generated from patients not residing in Yinzhou district; and (2) patient-sharing relationships not occurring in the same year (e.g., a physician provided care to this patient in a year while the other physician only provided care to this patient in the other year).

Networks Construction

We constructed physician networks by identified relationships between physicians if one patient had visit both of them within the same year. Specifically, we first constructed the bipartite network composed of physician-patient connections by extract the outpatient visit records within a year and generated the adjacency matrix of bipartite network (**Figure 1-a**).[40] Then, we constructed the physician-physician unipartite network by multiplying the adjacency matrix of bipartite network with its transpose.[45] The elements in the matrix of unimodal network were the number of patients shared between two physicians, which represented the strength of their relationship (**Figure 1-b**). The threshold of network was defined as the minimum strength of patient-sharing relationships needed to form a physician connection. For instance, "threshold = 2" indicated that two physicians would need to share at least two patients to be regarded as in a network. In the analysis, we did not apply a fixed threshold; instead, we tested multiple thresholds from 1 to 9 (range was determined based on previous report and validation) to identify stable patient-sharing relationships and reduce the impact of incidental connections that have a lower probability of knowledge exchange.[27, 39]

Measurements and Covariates

The main outcome of the analysis was the persistence of the physician-physician connections in the patient-sharing network, defined as the physician relationship in a given year continued to exist in the following year.[23] We used the persistence ratio, which refers to the proportion of remained relationships, to measure the degree of persistence. For instance, if ten pairs of patient-sharing relationships were observed in 2008 and eight of them

persisted to 2009, the one-year persistence ratio would be 80%. Connections that persisted for two or more years were seen as long-term relationships that could diffuse knowledge more intensely and thus have a larger effect on prescribing behaviors of the physicians involved.[29]

Many factors have been reported the association with persistence of patient-sharing relationships.[24, 29] We included the tie characteristics, physician specialty, strength of the relationship, and when such relationships occurred as covariates in our analysis, based on previous literature, theoretical framework of diffusion, and data availability. Tie characteristic was a binary variable reflecting whether the patient-sharing relationship happened within one or across multiple hospitals. A patient-sharing relationship was also classified according to specialties involved and assigned to a category of the followings: "PCPs- PCPs", "PCPs-Specialists", and "Specialists-Specialists". The year when patient-sharing relationship occurred was defined as the year when the outpatient visit (signaling a patient-sharing relationship) happened. Based on previous literature, we assumed that the knowledge translation and diffusion across years and hospitals could promote coordination of PCPs and specialists and subsequently improve healthcare system efficiency. Detailed variable selection and definition are reported in **Table 1**.

Statistical Analysis

We conducted logistic regression to analyze factors associating with the persistence of patient-sharing relationships, with the 95% confidence interval (CI) and P-value reported for each odds ratio (OR).[46] We applied logistic regression rather exponential random graph models (ERGM) as we primarily focused on assessing the strength and persistence of the physicians' relationships already identified, rather than examining the formation of the network. Strength ∈ [1 , 3), " Tie characteristics " = "no", " Physician specialty " = " PCP - PCP", and the year of 2010 were set as reference group in the regression. To visualize the structure of the patient-sharing network, we chose the Fruchterman-Reingold algorithm, a spring-embedder method, to present the physician network, with two physicians having stronger patient-sharing relationship lying closer in the illustration.[40, 47] In the analysis of

the persistence ratio of patient-sharing relationships, we conducted a sensitivity analysis based on thresholds and years of persistence of patient-sharing relationships; in the analysis of the factors of patient-sharing relationships, we conducted sensitivity analyses on the one-, two-, and three-year persistence to test the robustness of the findings. All analyses were performed using R 4.0.4, a two-sided P value < 0.05 was considered statistically significant.

Patient and public involvement

Patients and the public were not involved in this study.

Results

Study sample

Our final sample included 27,267 hypertensive patients and 3,916 physicians from 42 public healthcare facilities. The median and range of number of patients, physicians, and public healthcare facilities each year are described in **Table 2**. Overall, the median of physicians included according to the inclusion criteria was 1572 (Range 1264-2106) from 2010 to 2018, including 68.1% (54.5%-77.5%) PCPs and 31.9% (22.5-45.5%) specialists. The detailed number of samples from 2010 to 2018 was reported in **eTable 1**.

Structure of patient-sharing network

The patient-sharing network is visualized in **eFigure 1**. Overall, the median number of patient-sharing relationships (i.e., physician ties) was 67203 (Range 36543-89463) from 2010 to 2018, while the median number of relationships per physician was 41.7 (28.9-44.4, **Table 3 and eTable 2**). Among these ties, 70.8% (67.3%-74.1%) happened between physicians from different health care institutions (HCIs) while others were between physicians from the same HCI. The majority (55.1% [47.9%-60.9%]) of observed connections were between PCPs, 34.0% (30.9%-38.1%) were between PCPs and specialists, and 9.9% (8.2%-14.4%) were between specialists.

Most (68.9% [67.9%-75.3%]) observed connections had a strength ∈ [1, 3) (i.e., the two physicians had one or two tie(s)), only 10.7% (9.5%-11.4%), 4.7% (3.6%-5.3%), and 2.7% (2.0%-3.0%) had a strength ∈ [3, 5) (i.e., the two physicians had 3 or 4 ties), strength ∈ [5, 7), and strength ∈ [7, 9). There are many patient-sharing relationships had a strength ≥ 9 (12.5%[9.5, 13.1]). The network characteristics at different thresholds were reported in the **eTable 3**. Overall, the network diameter from 2010 to 2018 ranged from 6 to 9 for thresholds from 1 to 9; the network density ranged from 0.18 to 0.55 for thresholds from 1 to 9; the clustering coefficient ranged from 0.33 to 0.45 for thresholds from 1 to 9.

Persistence of patient-sharing network

Changes in the persistence of patient-sharing relationships for different network thresholds are shown in **Figure 2**. When threshold equaled 1, relationships seemed random and displayed trends vastly different from those shown when other thresholds were applied. When threshold was set at 3 (i.e., only patient-sharing relationships with strength⩾3 were retained), the physician network demonstrated a gradually downward trend as compared with when threshold was set at 1. Patient-sharing relationships showed similar patterns when the threshold was set at 3, 5, 7, or 9, with at least 80% of the relationships persisting after one year (Threshold=3: 81.8%, Threshold=5: 85.8%, Threshold=7: 86.9%, and Threshold=9: 87.4%) and at least 60% of the relationships persisting after three years (Threshold=3: 60.4%, Threshold=5: 64.4%, Threshold=7: 66.1%, and Threshold=9: 66.5%).

Factors associating with the persistence of patient-sharing network

Results of the logistic analysis of the factors associating with the persistence of patient-sharing relationships are shown in **Table 4**. We found the increase of strength of the relationships was associating with the increase of persistence of the relationships. Compared with the relationships that had a strength ∈ [1, 3), OR was 3.987 (95% CI: 3.896-4.08) for relationships with a strength ∈ [3, 5) was 3.987 (95% CI: 3.896-4.08), 6.379 (95% CI: 6.147-6.626) for relationships with strength ∈ [5, 7), and 8.373 (95% CI: 7.941-8.829) for relationships with strength ∈ [7, 9). Physicians from the same HCI were more likely to form connections that persisted at least one year

compared with physicians from different HCIs (OR=1.510, 95% CI: 1.480-1.540). PCP-Specialist relationships and Specialist-Specialist relationships had lower rates of one-year persistence compared with the PCP-PCP relationships (OR<1, p<0.001).

Sensitivity analysis of patient-sharing networks

We conducted a sensitivity analysis using two-year and three-year ties. Results of the sensitivity analysis confirmed that the strength of the relationship, tie characteristics, and physician specialty were important factors associating with the persistence of physician's patient-sharing relationships. (**Table 4**)

Discussion

This study provides insights into how frequently physicians in China fostered relationships with each other through delivering care to a shared patient and how strong and persistent these relationships were. We found that over 80% of physician relationships formed through sharing patients persisted over a year and 60% of these relationships persisted over three years, a result comparable to results from developed countries.[29] The strength of the relationship, tie characteristics, and physician specialty were important factors associating with the persistence of the physician's patient-sharing relationships. To our knowledge, this study is the first to describe the structure and influencing factors of the patient-sharing network among physicians engaged in the management of NCDs in a developing country. These findings suggest that physicians' patient-sharing networks can serve as a stable and viable target for future studies or interventions to promote care coordination and knowledge diffusion in China.

We observed that physician relationships were more persistent as the relationship threshold increased, which aligned with observations from previous studies.[23, 39] This suggests that physicians with more shared patients may be more likely to form a more stable professional relationship and demonstrate a great relationship persistence, thereby exerting profound influence on knowledge diffusion within the network.[24] Enhanced knowledge diffusion and information exchange strengthen the quality and coordination of healthcare services, as evidenced by reduced

emergency room visits and lower medical costs for patients treated by physicians persistent connection.[29, 48] This effect may also expend across physicians from different hospitals, to produce desirable patient outcomes, including lowered odds of readmissions and adverse events.[39, 49-51] Therefore, it is feasible to improve the relationship strength and improve healthcare quality by fostering physicians' professional network and promoting regular physician communication among providers.

In middle-income countries like China, the burden of cardiovascular diseases were more inequitably distributed than high-income countries, which is often exacerbated by a severe under-resource of personnel with expertise in and infrastructure supporting the management of cardiovascular diseases.[16] Developing interventions that utilize patient-sharing networks already present in physicians' day-to-day practices and that strengthen the hierarchical medical system can be an effective and cost-saving approach to influence physicians' behaviors, improve their coordination, and promote patient outcomes. As patient-sharing relationships formed among physicians of different HCIs can diffuse knowledge and influence their prescribing behavior, they can be utilized to promote the optimization of patient treatment plans to reduce patient burden and improve clinical outcomes in managing NCDs like hypertension.[13, 18, 48]

Our study confirmed that physicians both from primary care facilities were more likely to form and keep patient-sharing relationships, a result similar to a previous study.[52] The finding implied the less cohesive care coordination across different level of facilities in Chinese healthcare system,[53] may lead to suboptimal care continuity and disease control.[54] These relationships among physicians across different level of HCIs and specialties could lend insight into the barriers and promoters of an efficient healthcare system.[55] They are conducive to the knowledge diffusion beyond one single HCI, which has the potential to spread clinical treatment experience to improve quality of care in primary health care facilities, where physicians normally have less clinical capacity.[18] This is supported by a previous study which found that high value of network statistics, reflecting global connectivity, is beneficial to medical cost savings.[30] In contrast, hospitals with greater dispersion were

associated with greater rates of readmission and lower rates of emergency department throughput.[30, 56] Patient-sharing relationships among physicians can be a clear target to develop network-based interventions to curb these unfavorable outcomes.

The Chinese government has launched a hierarchical medical system policy in 2014, aiming to alter patients' healthcare-seeking behaviors. After its implementation, most patients are expected to first visit primary care facility, which ideally should be the same facility to ensure consistency in care. This redirection of patient flow to primary care facilities may cause PCPs to share patients more frequently, and thus more physicians could have more possibility to form more strength patient-sharing relationships.[54] We also found that the proportion of patient-sharing relationships formed between physicians practicing at the same HCI was lower than that reported in developed countries.[40, 57, 58] This may imply that HCIs in China have not established a harmonized patient referral system and thus patients frequently move between HCIs when certain needs remained unmet, which helped to form physician connections across HCIs.[59] A previous study has found that PCPs has a central role in managing chronic diseases and a hierarchical medical system can leverage the management of NCDs.[42] Our another study has confirmed in the increased persistence of patient-sharing relationships cross different healthcare levels since 2015, when the hierarchical medical system policy was implemented in China. which attributed to the policy's promotion of primary care physician's centrality in disease management.[54]

There are several limitations to this study. First, we established the social network of physicians based on a database from a single district in China, thus our result may not be generalized to other areas in China with different physician network structures. Additionally, we were unable to observe the actual patient flow and the dynamics of these relationships from the retrospective data. A fuller landscape of the impact of knowledge diffusion through these relationships on physicians' prescribing behaviors may only be gained through conducting qualitative studies in the future. Second, we limited the disease area to hypertension to represent the characteristics of the patient-sharing network of physicians managing NCDs. However, physician networks may be affected by

differences in chronic diseases, such as patient characteristics, which were unable to incorporate in this study. For instance, the differences in severity of the disease or co-morbidities may lead to distinct patient visiting pattern, thus our results should be interpreted within the specific context. Third, we only constructing network using the one-year time frame to identifying physicians' relationship. Though there was study observing that shorter time frames do not significantly affect the results,[60] it is possible that the results could be different if we change the time frames in our setting. Future research should consider constructing networks over different time frames as data permit. Forth, our association analysis may subject to unmeasured confounding bias since we failed to include additional physician factors potentially associating with the persistence. For instance, factors such as physicians' practicing department, years in practice, or professional title were not included, whereas it is possible that physicians may be more likely to establish connections with others who shared similar characteristics.[61] Future research should consider incorporating relevant factors more comprehensively or applied methods such as instrumental variables to effectively control for potential confounding. Last, we have not examined the relationship between the persistence of physician relationships and patient health outcomes, which holds greater clinical and policy relevance. Future research should focus on this topic to offer novel insights for healthcare policy and practice, especially on leveraging physicians' social networks to improve healthcare delivery.

Conclusions

We found that physicians frequently formed relationships with other physicians through sharing patients in Yinzhou, China. These relationships showed similar rates of persistence to studies conducted in developed countries, where network-based interventions have been proven effective in curbing some problems in healthcare delivery and patient outcomes. Future research and interventions to promote care coordination and knowledge diffusion can leverage these naturally occurring relationships and seek to understand mechanisms through which they can exert influences on healthcare providers' practices and coordination with one another.

Declarations

Ethics approval and consent to participate

Ethical approval was obtained from the Peking University Medical Ethics Committee (IRB00001052–22052). Requirement of informed consent for participation was exempted for this study according to the national legislation and the institutional requirements.

Authors' contributions

Zhiwen Gong: Software, Formal analysis, Writing- Original draft preparation; **Ruilin Wang**: Software, Formal analysis, Writing- Original draft preparation; **Huajie Hu**: Data Curation, Software, Formal analysis, Writing- Original draft preparation; **Tao Huang**: Data Curation, Validation, Writing - Review & Editing; **Huangqianyu Li**: Writing - Review & Editing; **Sheng Han**: Conceptualization, Supervision, Writing - Review & Editing; **Luwen Shi**: Conceptualization, Supervision, Writing - Review & Editing; **Xiaodong Guan**: Conceptualization, Supervision, Writing - Review & Editing, Funding acquisition.

All authors gave final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately.

Guarantor: **Xiaodong Guan**

Conflicts of Interest

The authors declare that they have no competing interests.

Abbreviations

YHIS: Yinzhou Health Information System

NCDs: non-communicable diseases

PCPs: Primary Care Physicians

CI: confidence interval

OR: odds ratio

HCIs: Health Care Institutions

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472 **Table 1.** Variable selection and definition in the analysis of patient-sharing relationship in Yinzhou

Variable	Definition	Meaning
Persistence ratio	The proportion of the patient-sharing relationships in a given year that continue to exist in the following year.	Reflecting long-term relationships across years, and the professional knowledge may diffuse through the network and have an effect on the physicians' prescription behavior.
Relationship strength	The number of the sharing patients between physicians.	Representing a more stable patient-sharing relationship, higher persistence ratio and long-term patient-sharing relationships have positive effects on knowledge diffusion in the network.
Hospital characteristics	Whether the related physicians of patient-sharing relationship from the same hospital.	The patient-sharing relationships among different physician specialties are conducive to the Representing whether knowledge diffusion in a same geographical area, helpful to the update of clinical treatment experience.
Physician specialty	The specialty of the related physicians of patient-sharing relationship.	Regions with higher persistent ties tended to have lower rates of emergency medical visits, and regions where PCPs had more physician connections were more likely to have higher emergency medical visits.
Relationship occurrence year	The year of the visit when the physician-sharing relationship happened.	The impact of occurrence year on the patient-sharing relationships could help to understand the trend and other influencing factors on the patient-sharing relationships (e.g., policy factors etc.) could help to explore and assess the network-based interventions.

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Table 2. Number of sampled patient and physicians constructed physician network for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

Number of samples	Median	Range
Number of patients	129021	(77063, 181997)
Number of hospitals		
Total	29	(25, 41)
Primary care facilities	25	(22, 33)
Secondary hospitals	1	(1, 3)
Tertiary hospitals	3	(2, 5)
Number of physicians		
Total	1572	(1264, 2106)
Primary care facilities	1070	(948, 1287)
Secondary hospitals	77	(54, 153)
Tertiary hospitals	440	(230, 703)

Table 3. Characteristics of patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

Number of observed connections	Median	Range
Total	67203	(36543, 89463)
Hospital		
Not in same hospital	47896	(24587, 64089)
In same hospital	19307	(11956, 25374)
Physician specialty		
PCP - PCP	37182	(22272, 47477)
PCP – Specialist	22877	(11285, 30093)
Specialist - Specialist	6534	(2986, 11893)
Strength of connections		
[1,3)	46330	(24871, 67378)
[3,5)	7073	(4101, 8484)
[5,7)	3099	(1937, 3292)
[7,9)	1817	(1054, 2002)
≥9	8339	(4580, 9187)

(Note) PCP: Primary Care Physicians.

Table 4. Logistic regression of persistent ties for patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

	One-year persistent ties		Two-year persistent ties		Three-year persistent ties	
	OR	95% CI	OR	95% CI	OR	95% CI
Strength						
[1,3)	Reference	-	Reference	-	Reference	-
[3,5)	3.987 ***	(3.896, 4.08)	3.203 ***	(3.13, 3.274)	2.790 ***	(2.724, 2.858)
[5,7)	6.379 ***	(6.147, 6.626)	4.716 ***	(4.563, 4.874)	3.796 ***	(3.669, 3.924)
[7,9)	8.373 ***	(7.941, 8.829)	6.019 ***	(5.755, 6.29)	4.614 ***	(4.424, 4.816)
≥9	11.965 ***	(11.6, 12.354)	8.290 ***	(8.077, 8.508)	6.184 ***	(6.032, 6.341)
Hospital characteristics						
Not in the same hospital	Reference	-	Reference	-	Reference	-
Same hospital	1.510 ***	(1.48, 1.54)	1.402 ***	(1.373, 1.43)	1.358 ***	(1.33, 1.385)
Physician specialty						
PCP - PCP	Reference	-	Reference	-	Reference	-
PCP – Specialist	0.876 ***	(0.862, 0.891)	0.693 ***	(0.68, 0.705)	0.555 ***	(0.544, 0.567)
Specialist - Specialist	0.566 ***	(0.55, 0.582)	0.463 ***	(0.45, 0.476)	0.384 ***	(0.373, 0.396)
Year						
2010	Reference	-	Reference	-	Reference	-
2011	0.803 ***	(0.779, 0.826)	0.854 ***	(0.829, 0.879)	0.937 ***	(0.909, 0.965)
2012	0.826 ***	(0.803, 0.85)	0.914 ***	(0.888, 0.94)	1.035 ***	(1.005, 1.065)
2013	0.791 ***	(0.768, 0.813)	0.905 ***	(0.88, 0.931)	0.696 ***	(0.676, 0.716)
2014	0.811 ***	(0.789, 0.834)	0.599 ***	(0.583, 0.617)	0.429 ***	(0.416, 0.442)
2015	0.510 ***	(0.496, 0.524)	0.379 ***	(0.368, 0.39)	0.221 ***	(0.214, 0.228)

(Note) PCP: Primary Care Physicians. One-year persistent ties represent ties that generating in one year and persist in the next year, two-year represents persisting in next two years, and three-year represents persisting in next three years, when considering the three-year persistent ties, the ties generating in 2015 that persists in 2018, therefore the year of 2016, 2017, and 2018 were unobservable.

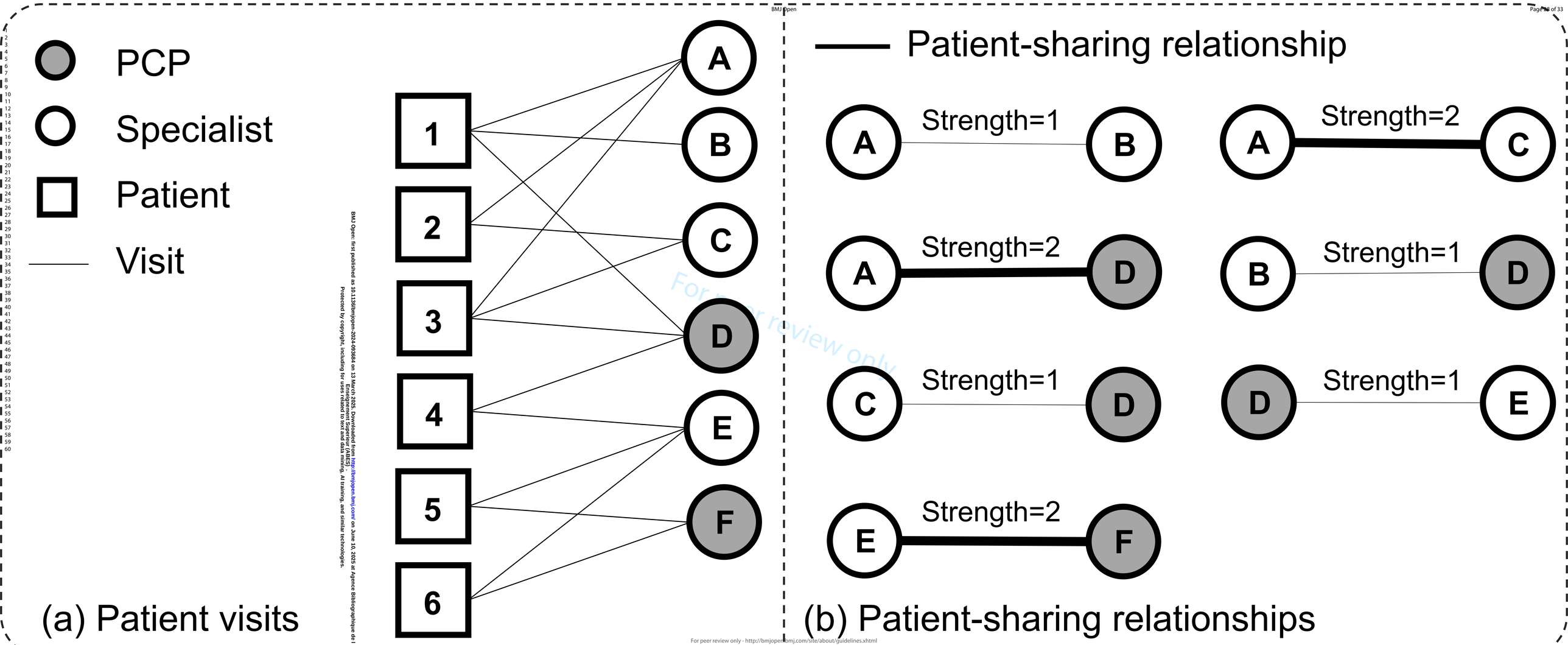
*** p<0.001, ** p<0.01, * p<0.05

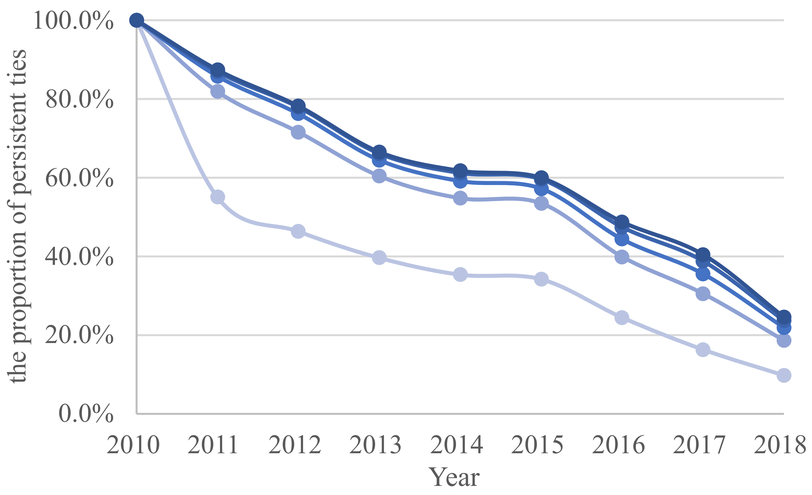
Figure 1. Schematic diagram of the patient-sharing relationships

(Note) PCP: Primary Care Physicians. Node: physicians in the network; Tie: the connections between physicians in patients-sharing relationships; Strength: the weight of the ties between the two nodes, refers to the number in patients-sharing relationships.

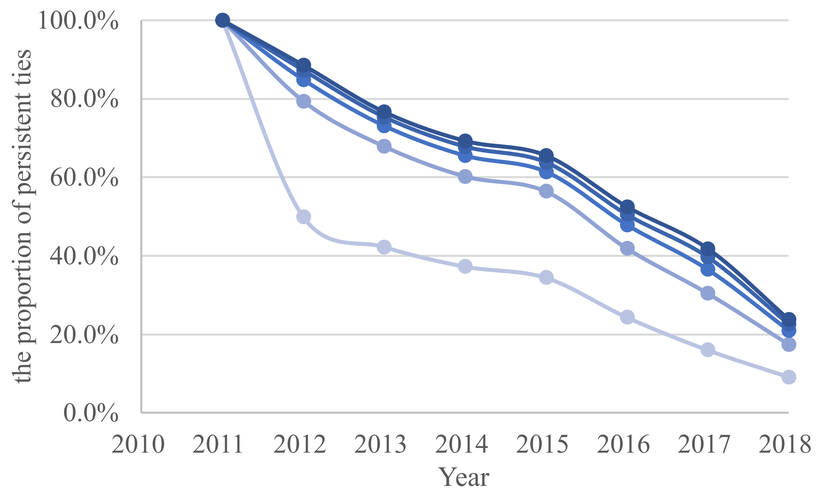
Figure 2. The proportion of persisitent ties for patient-sharing relationships for medication therapy management of hypertension patients in Yinzhou from 2010-2018

(Note) Part (a)-(h) represents the proportion of persistent ties generating in 2010-2018, respectively.

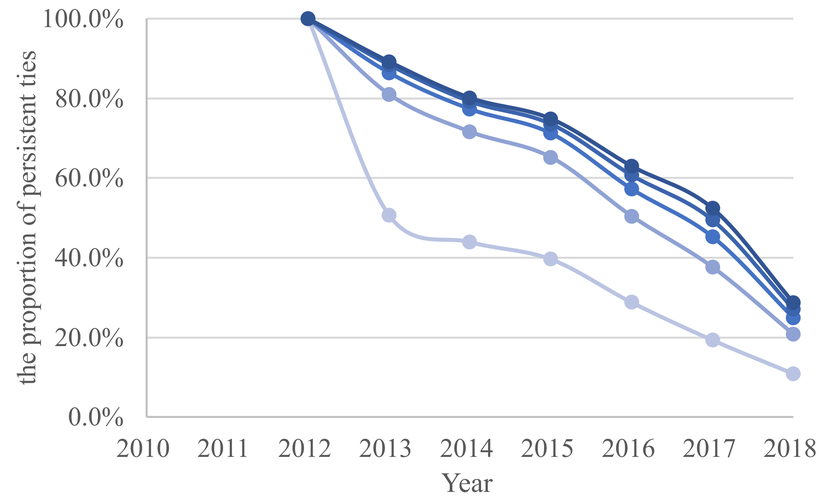




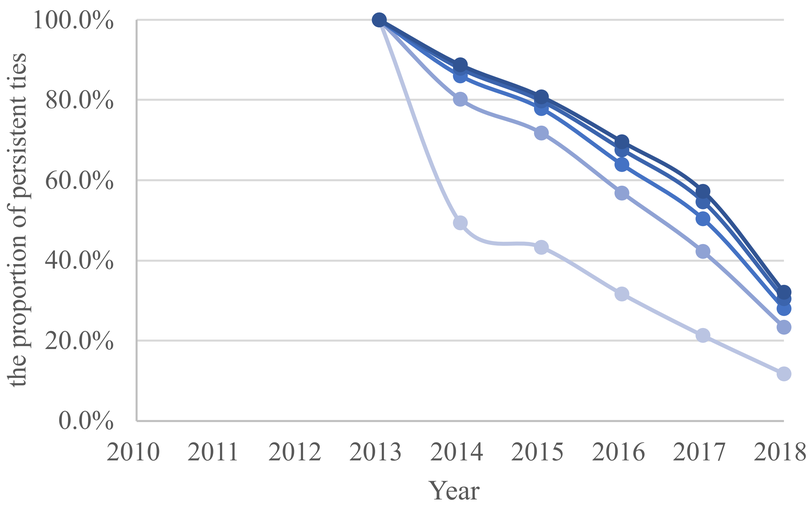
(a) Patient-sharing relationships in 2010



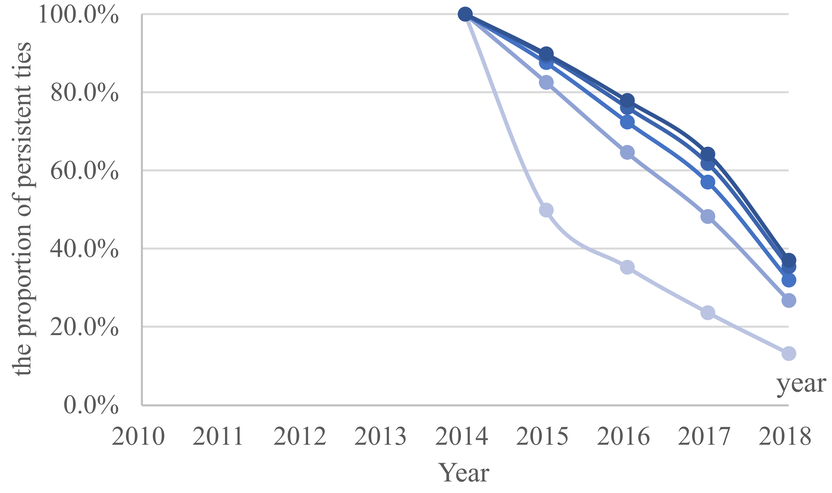
(b) Patient-sharing relationships in 2011



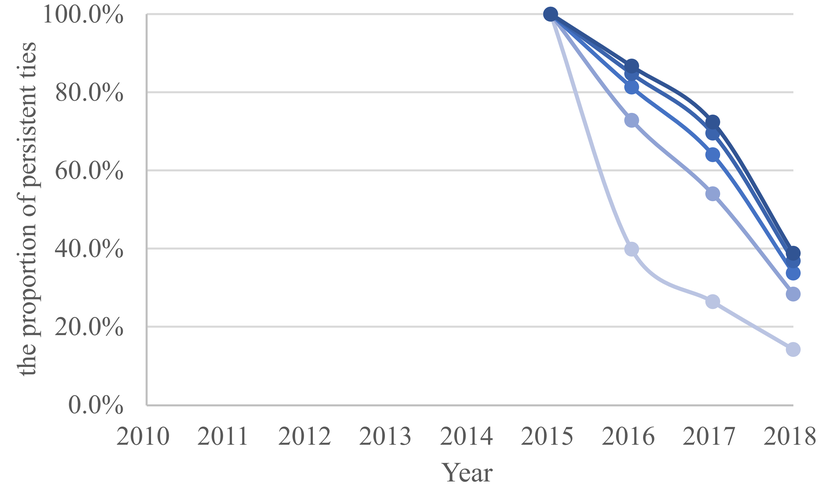
(c) Patient-sharing relationships in 2012



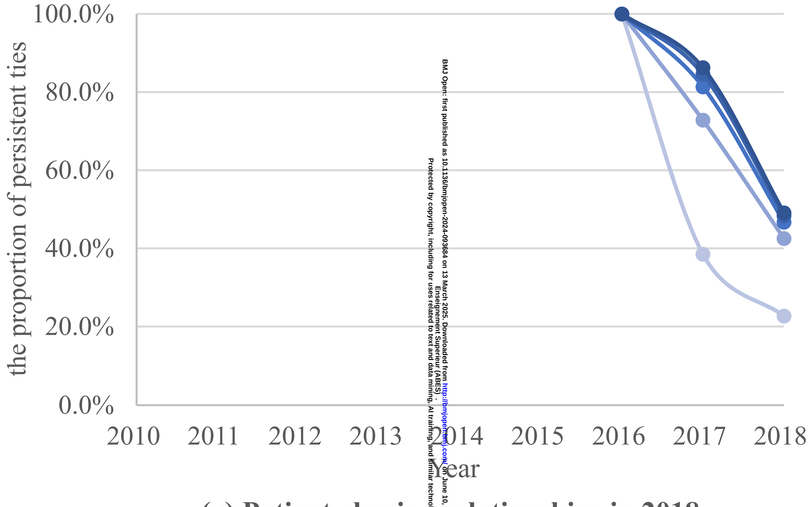
(d) Patient-sharing relationships in 2013



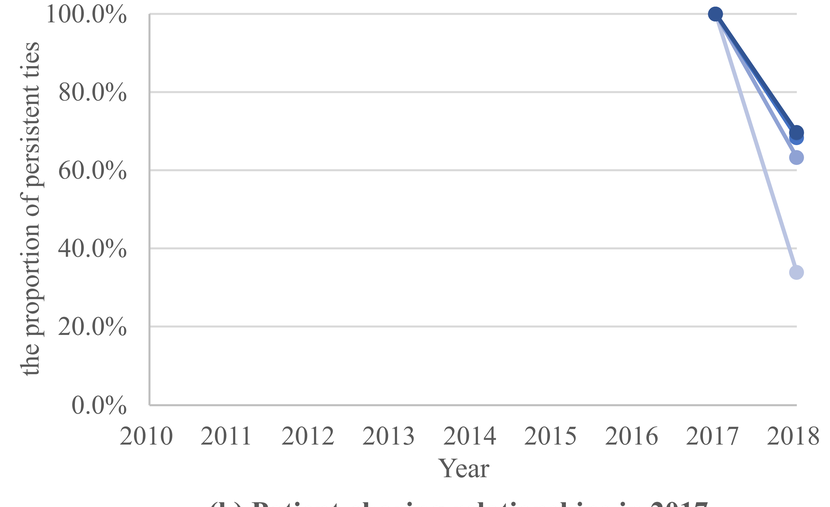
(e) Patient-sharing relationships in 2014



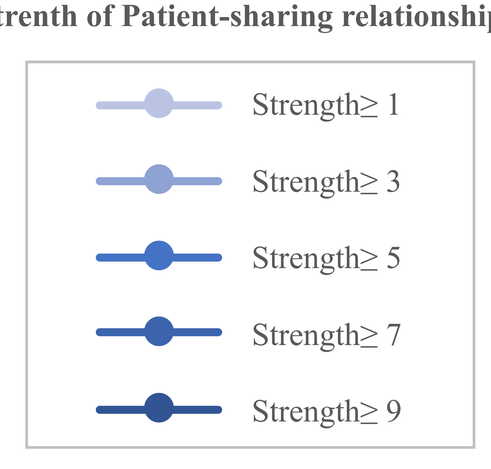
(f) Patient-sharing relationships in 2015



(g) Patient-sharing relationships in 2018



(h) Patient-sharing relationships in 2017



Supplementary Materials

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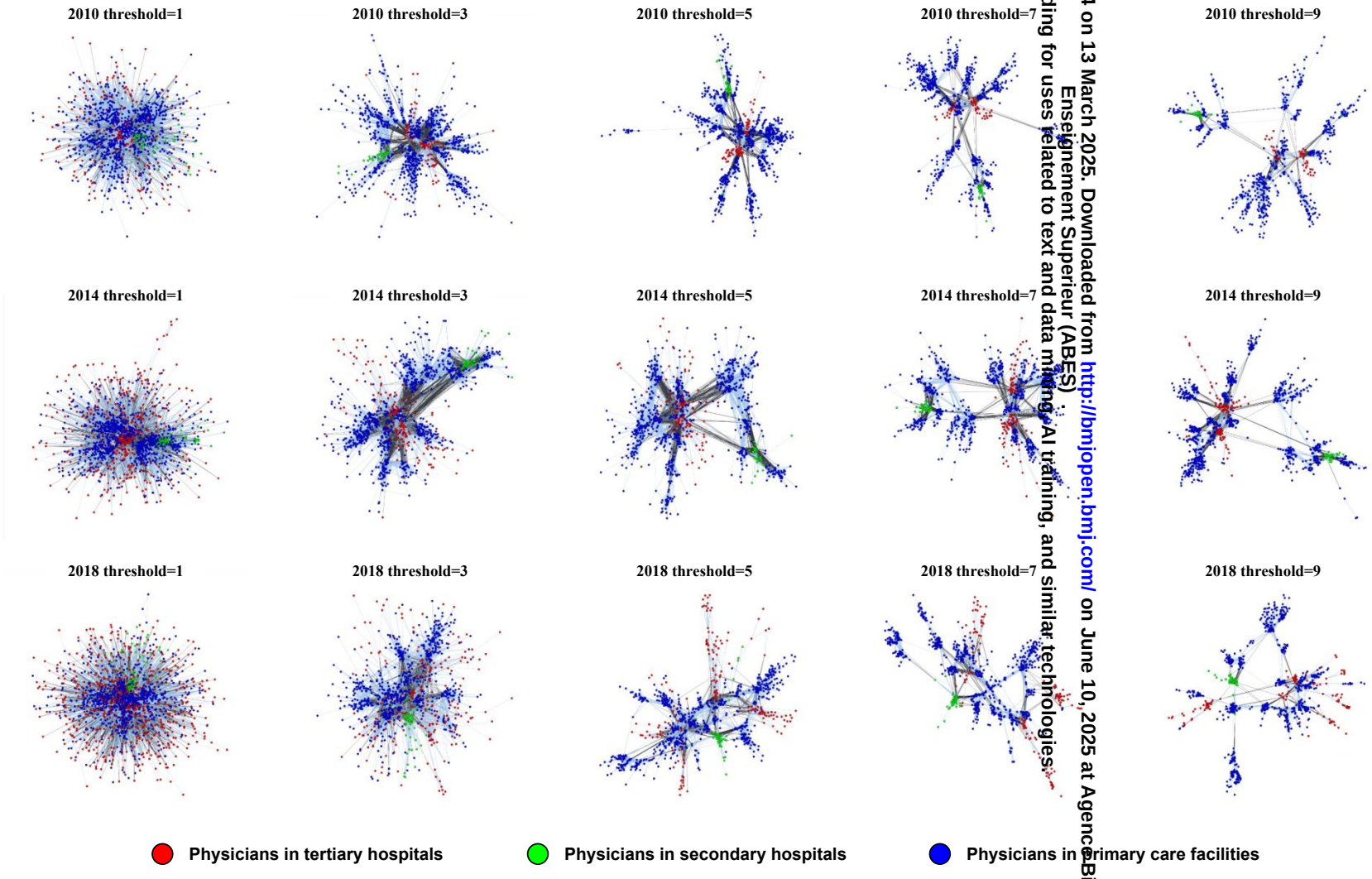

eFigure 1. Structure of physician network for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

eTable 1. Number of sampled patient and physicians constructed physician network for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

Number of samples	Year								
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Number of patients	77063	97187	110507	119920	129021	135957	150239	181997	137582
Number of hospitals									
Total	25	26	28	28	29	29	31	41	33
Primary care facilities	22	23	25	25	25	25	26	33	26
Secondary hospitals	1	1	1	1	1	1	2	3	2
Tertiary hospitals	2	2	2	2	3	3	3	5	5
Number of physicians									
Total	1264	1384	1475	1514	1572	1679	1898	2106	1739
Primary care facilities	980	1024	1084	1072	1070	1089	1060	1287	948
Secondary hospitals	54	59	68	77	62	90	153	145	88
Tertiary hospitals	230	301	323	365	440	500	685	674	703

eTable 2. Characteristics of patient-sharing relationships for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

Number of observed connections	Year								
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Total	36543	55934	61509	66206	67203	74541	79029	89463	68610
Hospital									
Not in same hospital	24587	39022	43211	46304	47896	53831	55977	64089	50851
In same hospital	11956	16912	18298	19902	19307	20710	23052	25374	17759
Physician specialty									
PCP - PCP	22272	30816	35422	37182	38386	38401	37818	47477	36571
PCP – Specialist	11285	19599	20703	22490	22877	28381	29807	30093	23805
Specialist - Specialist	2986	5519	5384	6534	5940	7758	11404	11893	8234
Strength of connections									
[1,3)	24871	38008	41785	45376	46330	52183	57503	67378	51649
[3,5)	4101	6398	6953	7324	7073	7982	7470	8484	6594
[5,7)	1937	2904	3028	3284	3176	3233	3099	3292	2481
[7,9)	1054	1652	1826	1883	1830	2008	1795	1817	1370
≥9	4580	6972	7917	8339	8794	9185	9162	8492	6516

(Note) PCP: Primary Care Physicians.

eTable 3. Network characteristics of physician network for medication therapy management of hypertensive patients in Yinzhou from 2010-2018

Network Characteristics	Network threshold	Year								
		2010	2011	2012	2013	2014	2015	2016	2017	2018
Number of nodes (physicians)	1	1264	1384	1475	1514	1572	1679	1898	2106	1739
	3	974	1089	1161	1183	1167	1240	1298	1477	1114
	5	885	1008	1076	1093	1053	1128	1168	1314	976
	7	827	960	1020	1035	997	1045	1099	1231	908
	9	780	929	967	987	955	1000	1057	1166	858
Number of ties (physicians' connection)	1	36543	55934	61509	66206	67203	78241	79029	89463	68610
	3	11672	17926	19724	20830	20873	24811	21526	22085	16961
	5	7571	11528	12771	13506	13800	16123	14056	13601	10367
	7	5634	8624	9743	10222	10624	12189	10957	10309	7886
	9	4580	6972	7917	8339	8794	9787	9162	8492	6516
Network diameter	1	5	5	5	5	6	6	5	6	6
	3	6	6	6	6	6	6	7	6	7
	5	7	7	7	7	6	6	7	10	8
	7	9	8	8	9	7	7	7	15	10
	9	9	10	10	9	9	9	9	9	11
Network density	1	0.049	0.060	0.057	0.058	0.055	0.055	0.044	0.041	0.046
	3	0.027	0.031	0.030	0.030	0.031	0.030	0.026	0.020	0.028
	5	0.022	0.024	0.023	0.023	0.025	0.025	0.021	0.016	0.023
	7	0.019	0.020	0.020	0.019	0.022	0.021	0.018	0.014	0.021
	9	0.020	0.017	0.018	0.018	0.020	0.020	0.017	0.019	0.019
Clustering coefficient (transitivity)	1	0.330	0.335	0.333	0.331	0.328	0.325	0.304	0.293	0.321
	3	0.360	0.354	0.363	0.363	0.366	0.376	0.384	0.377	0.393
	5	0.389	0.368	0.388	0.390	0.402	0.413	0.451	0.443	0.471
	7	0.425	0.391	0.409	0.413	0.428	0.439	0.484	0.484	0.525
	9	0.447	0.415	0.436	0.442	0.448	0.457	0.508	0.507	0.560