Original Article

China's landscape in oncology drug research: perspectives from research collaboration networks

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Objective: Better understanding of China's landscape in oncology drug research is of great significance for discovering anti-cancer drugs in future. This article differs from previous studies by focusing on Chinese oncology drug research communities in co-publication networks at the institutional level. Moreover, this research aims to explore structures and behaviors of relevant research units by thematic community analysis and to address policy recommendations.

Methods: This research used social network analysis to define an institutions network and to identify a community network which is characterized by thematic content.

Results: A total of 675 sample articles from 2008 through 2012 were retrieved from the Science Citation Index Expanded (SCIE) database of Web of Science, and top institutions and institutional pairs are highlighted for further discussion. Meanwhile, this study revealed that institutions based in the Chinese mainland are located in a relatively central position, Taiwan's institutions are closely assembled on the side, and Hong Kong's units located in the middle of the Chinese mainland's and Taiwan's. Spatial division and institutional hierarchy are still critical barriers to research collaboration in the field of anti-cancer drugs in China. In addition, the communities focusing on hot research areas show the higher nodal degree, whereas communities giving more attention to rare research subjects are relatively marginalized to the periphery of network.

Conclusions: This paper offers policy recommendations to accelerate cross-regional cooperation, such as through developing information technology and increasing investment. The brokers should focus more on outreach to other institutions. Finally, participation in topics of common interest is conducive to improved efficiency in research and development (R&D) resource allocation.

Keywords: Anti-cancer; pharmaceuticals; publications; research collaboration networks; thematic analysis

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Introduction

Cancer is one of the leading causes of death worldwide. According to the latest world cancer statistics released by the International Agency for Research on Cancer, there were 14.1 million new cancer cases and 8.2 million cancer-related deaths in 2012, with a substantive increase (56.8% cancers and 64.9% cancer deaths) in less-developed countries. These proportions are expected to increase by 2015 (1).

China, which has been equally affected by the cancer epidemic, has become the world's second-largest economy since 2010 with dramatic growth of its Gross Domestic Product (GDP) in the past three decades (2). This economic growth has greatly stimulated the development of science and technology in China. The country's Gross Expenditure on Research and Development (GERD) reached 1.98% of its GDP in 2013 (from 0.73% in 1991) (3). China has become the second-largest sponsor of global research and development (R&D), measured in terms of funding and generation of intellectual capital (4). The country contributed 12% of the world's scientific articles in 2013

[16.3% in the United States (U.S.)].

Furthermore, China is developing at an accelerated rate in the collective domain of science, technology, and innovation in the pharmaceutical sector, which is considered a powerful engine for sustainable economic growth (5). The Chinese government launched the project "Key Drug Innovation" in 2007, which provides R&D funding for the pharmaceutical sector. The project provided $1 billion during 2011-2015 and is expected to add investments to approximately $4.3 billion by 2020 (6,7). As an important national project, Key Drug Innovation aims to develop a series of innovative drugs for treating ten major diseases, including malignant tumors. Since the project's inception, China's anti-cancer drug research has been greatly impelled, while a series of related research results have emerged in the intentional community.

Several articles have been devoted to presenting oncology research in China in the last few years. Dai (2012) analyzed research articles in *China Cancer* from the perspective of bibliometrics (8), while Yu (2011) explored co-authorship networks of oncology in China based on 10 core Chinese oncology journals (9). What seems to be lacking, however, is an analysis focusing on oncology research by Chinese scientists published in international journals, especially in terms of the dramatically increasing outflow of papers reflecting outstanding achievements in scientific research over the past few years (10,11). One exception is a bibliometric study by Zheng (2012), which analyzed oncology papers published by Chinese authors covered in the Science Citation Index Expanded (SCIE) from 2010-2012 (12). Zheng's article described a unique sample from the angle of journals, disciplines, countries, and partial institutions, but it ignored research collaborations between institutions and, thus, did not fully identify China's leading institutions in the field of anti-cancer drug research. This present work differs from previous studies by elaborating on communities in co-publication networks at the institutional level with an emphasis on the pharmaceutical research of oncology in greater China. Moreover, this research aims to construct organizational collaboration networks of Chinese oncology drug research by using co-publication data in leading international journals, to explore structures and behaviors of relevant research units by thematic community analysis, and to address policy recommendations.

Materials and methods

To access leading Chinese anti-cancer drug research, the data on publications were retrieved by subject, combining oncology and pharmacy or complementary medicines from the SCIE database of Web of Science, a high quality, multidisciplinary scientific information platform. The publication sample was refined by restricting the authors' addresses to China[1] and the time span to 2008-2012. The data retrieval process is illustrated in *Figure 1*.

There were 675 articles in accordance with search criteria in this study. The majority of document types in the data sample are research articles (93.09%); the rest is composed of review papers (5.44%) and other manuscripts (1.47%), such as proceedings or editorial letters. The articles are assigned to research areas, whereas all of them are classified to belong to oncology (100%); pharmacology and pharmacy occur for most articles (92.79%), while research experimental medicine, and radiology nuclear medicine and medical imaging turn out for about a quarter of all articles. The research area of integrative and complementary medicine is listed in 7.21% of the articles, pathology in 4.56% and immunology in 0.74%. Funding sources for the articles come mostly from national and social non-profit agencies. The top three funding sources are the National Natural Science Foundation of China (NSFC) (20.92%), the National High Technology Research and Development Program of China ("863 Program") (3.70%), and the National Basic Research Program of China ("973 Program") (2.61%). Universities, research institutions, hospitals and companies provide a rather low fraction of funds for the articles under consideration. For example, only 25 articles, accounting for 3.7% of total sample papers, exactly show funding sources including companies[2].

The bibliographic data, such as article title, keyword, author name, affiliated institution, and institution address, have been extracted from the 675 articles, producing a set of 342 Chinese research institutions, and giving rise to a co-publication network between them.

From the data, we first defined a network by means of graph theoretic approaches (13). This network was constituted by a set of nodes representing the 342 research institutions, and a set of links between institutions representing co-publication intensity. Full counting has

[1] In this study, China includes the Chinese mainland, Hong Kong, Taiwan, and Macao, to cover greater China.

[2] We recognize the influence of funding sources on research collaboration mode. It is, however, assumed that the effect of skewed funding sources on research results should be rather limited in view of the low percentage of company articles in the sample data. In addition, it is worth noting that funding information is not available for 229 articles (33.9%) where a potential bias may occur.

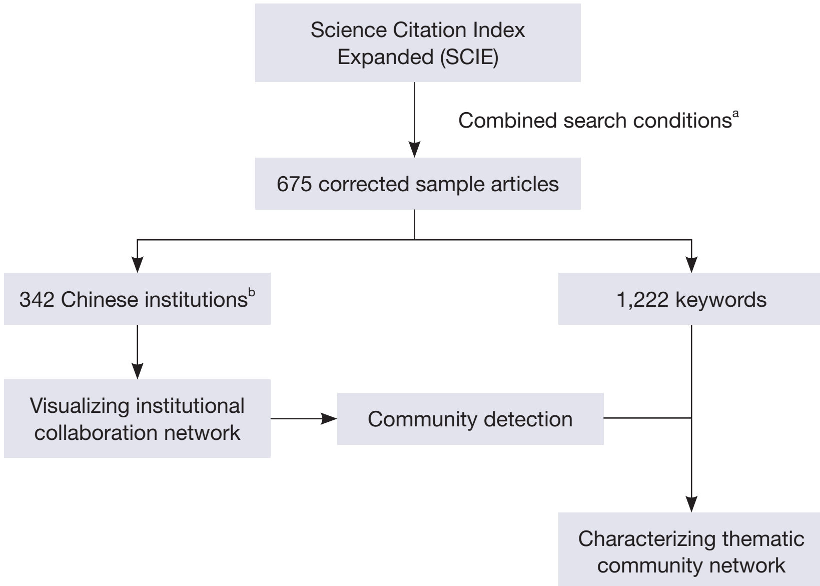

Figure 1 Flowchart of the research process. [a], Combined search conditions: "AD=(China or Taiwan or Hong Kong or Macau or Macao or Hongkong) and WC=[(Pharmacology & Pharmacy and Oncology) or (Integrative & Complementary Medicine and Oncology)] and Indexes=SCIE and Timespan=2008-2012". AD is a field tag for address and WC is Web of Science Category which is used to narrow search to specific fields of study; [b], Institutions were from the author information supplied by the 675 articles. Since the emphasis of this research is placed on collaborative linkages between Chinese units, records of authors belonging to a non-Chinese institute were removed. Besides, we standardized institutional affiliations supplied by the authors; SCIE, Science Citation Index Expanded.

been employed in this study, i.e., in case of articles with more than one co-author from one institution, all author-pair relationships are counted with a value of 1. In order to get some clues about the prominence of specific research institutions, centrality measures are calculated (14), including weighted degree and betweenness centrality. The centrality measures are used to provide quantitative insights on the role of specific research institution in the network, enabling us to produce a ranking of most prominent ones.

Additionally, we identified research collaboration communities using the network. A network community is a subnetwork whose nodes are more strongly connected to one another than to the rest of the network. To quantify this notion, we make use of the modularity (15), which is a measure that assigns a numeric value assessing how well a partition of the network nodes matches the informal notion of community. Further, by searching for node partitions that have a high modularity, it thus becomes possible to detect relevant communities in the network. To do this, we use the Louvain method (16), an efficient and widely used method for detecting high-modularity communities.

To characterize the thematic content of a given community, we used the keywords from papers in the community. For a subject keyword s in community c, we defined the ratio $R_{sc}=f_{sc}/f_s$, where f_{sc} was the fraction of papers in c with keyword s, and f_s was the fraction of all papers with keyword s (17). High R_{sc} values indicated keywords that were especially relevant to the community and that occurred more in the community than in article set as a whole.

Results

By measuring co-publication data in leading international journals, *Figure 2* visualizes institutional collaboration networks dedicated to anti-cancer drug research in China. These networks included 342 nodes and 5,168 weighted edges, which represented China's research institutions and collaboration links between them respectively. Node size reflected the unweighted degree of an institution (i.e., the number of neighbors of the institution by co-publication connection), while the strength of edges corresponded to edge weights measured by the frequency of co-publication between researchers of two institutions. Red nodes are the institutions located within the Chinese mainland, yellow

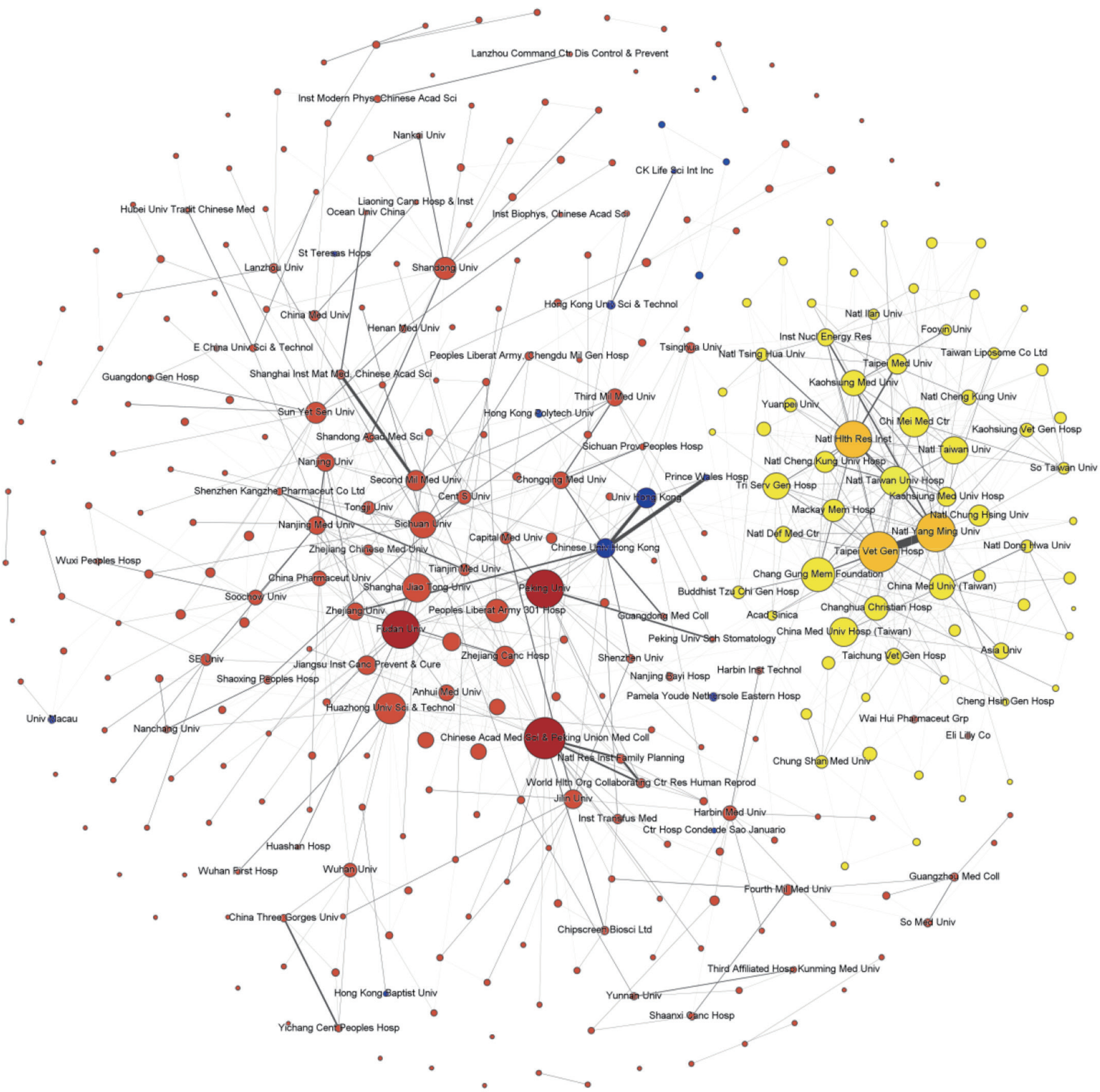

Figure 2 Institutional collaboration network of anti-cancer drug research in China. This network was visualized and analyzed by using Gephi that is an open-source software for complex systems analysis and visual exploration of networks (13). This figure is composed of 342 nodes and 5,168 weighted edges. A node represents a China's research institution and the node-size reflects the unweighted degree of an institution (i.e., the number of neighbors of the institution by co-publication connection). The strength of edges corresponds to edge weights measured by the frequency of co-publication between researchers of two institutions. Red nodes are the institutions located within the Chinese mainland, yellow are Taiwan's institutions, and blue are Hong Kong's and Macao's institutions. Moreover, some remarkable notes are labeled as abbreviation names of institutions.

are Taiwan's institutions, and blue are Hong Kong's and Macao's institutions, while the top six nodes by centralities are more darkly colored. Some remarkable nodes are labeled as abbreviation names[3] of institutions in the Web of Science database. Nodal positions were determined using the Fruchterman-Reingold (18) method so that strongly interconnected institutions were positioned nearer one another[4]. Based on the layout strategy, strongly connected institutions are placed in the central position in the network, whereas those with weak connections are on the periphery. In *Figure 2*, institutions based in the Chinese mainland are located in relative central position, while Taiwan's institutions are assembled on the right side, and institutions in Hong Kong are well integrated into whole networks with frequent interactive connections between the Chinese mainland and Taiwan.

To focus on notable institutions, *Table 1* presents top organizations with more than 100-weighted degree, which was defined as the frequency of co-publication of an organization. Obviously, weighted degree included two parts, internal co-publications within an organization as well as external links between the organization and others. The percentage of the latter part in weighted degree measured the level of external collaborations of an organization. On the other hand, the betweenness centrality represented institutional importance to other institutions' virtual communications by measuring the extent to which an institution was located between other institutions.

As a result, *Table 1* covers institutions based in the Chinese mainland, Hong Kong, and Taiwan. Particularly, institutions in the Chinese mainland are mainly composed of "Project 985" universities, a Chinese initiative aimed at supporting a number of top universities in establishing worldwide notoriety. Institutions in Hong Kong and Taiwan seemed more active in developing external collaborations, as is clearly shown by their higher level of external collaborations (LEC) percentages. Sichuan University appeared to be a strong but closed player in the development of novel oncology pharmaceuticals, as was revealed by its first position by weighted degree and low LEC value. It is noteworthy that Peking University jumped to the first place measured by betweenness centrality. This indicated the importance of Peking University as a gatekeeper or broker, influencing research collaborations between other institutions. Subsequently, the Chinese Academy of Medical Sciences & Peking Union Medical College, Chang Gung Med Foundation, Huazhong University of Science & Technology, Sichuan University, and Jilin University, which were scattered in different geographic regions in China, showed strong betweenness performance.

From previous research (19), we know that we should consider not only the absolute but also the relative strength of the links between nodes (i.e., institutions). The Jaccard index[5] (20) provides an appropriate measure to capture the relative size of the cross-institution collaborative links. In our study, the index is defined as

$$J_{ij} = \frac{F_{ij}}{\sum_{j=1}^{n} F_{ij} + \sum_{i=1}^{n} F_{ij} - F_{ij}} \qquad i, j = 1, \ldots, n; i \neq j \qquad [1]$$

where F_{ij} is the number of observed co-publication links between two institutions, *i* and *j*. Thus, F_{ij} and J_{ij} denoted absolute and relative strengths of co-publications between institutions *i* and *j* respectively. We have separately collected top 50 institutional pairs measured by absolute and relative values and selected the overlapping pairs between two rankings as top institutional pairs in the Chinese anti-cancer drug research network. The results are shown in *Table 2*.

The paired institutions mentioned in *Table 2* showed more solid collaborations on anti-cancer drug research in terms of absolute frequency and mutual dependence. Interestingly, most of the close partners (75%) are located within the same provincial-level administrative region and physically neighboring regions which are defined as those sharing a common border. The geographic proximity of close partners reflects that geographical space is one of the main barriers to research collaboration in the field of anti-cancer drug development in China.

Each high-modularity community was identified, and their research focuses based on keywords were analyzed to understand the essential structures and behaviors of each research network. These results are shown in *Figure 3*.

[3]Institution names in this article are shown as standard abbreviations in the Web of Science, which can be spelled out by the link, http://images.webofknowledge.com/WOKRS513R8.1/help/WOK/hp_address_abbreviations.html.

[4]The Fruchterman-Reingold method uses a physical analogy to determine the placement of network nodes. Nodes repel one another, like electrically charged particles, while links cause attraction, like springs. Solving for a static equilibrium in the resulting force equations results in a set of node positions where strongly interconnected sets of nodes are placed near one another.

[5]The Jaccard index is used to measure mutual-dependence degree between the organizations in a collaboration pair and a number between 0 and 1. It is closer to 0 when the units have lower dependence and closer to 1 when they have higher mutual-dependence.

Table 1 Top institutions ranked by weighted degree

Rank	Organizations*	WD (LEC%); BC	Rank	Organizations	WD (LEC%); BC
1	Sichuan Univ	1,026 (14.3); 6,087	26	Huazhong Univ Sci & Technol	225 (31.1); 6,607
2	Zhejiang Univ	768 (18.1); 2,167	27	Chongqing Med Univ	209 (54.5); 1,353
3	Chinese Univ Hong Kong (HK)	740 (55.7); 4,048	28	Natl Taiwan Univ Hosp (TW)	208 (85.6); 1,369
4	Fudan Univ	696 (25.3); 4,901	29	Natl Res Inst Family Planning	184 (83.2); 19
5	Natl Yang Ming Univ (TW)	672 (77.2); 2,169	30	Prince Wales Hosp (HK)	182 (69.8); 0
6	Peking Univ	643 (32.3); 10,747	31	Cent S Univ	174 (25.3); 730
7	Sun Yet Sen Univ	633 (18.8); 4,442	32	Kaohsiung Med Univ (TW)	171 (60.8); 236
8	Chinese Acad Med Sci & Peking Union Med Coll	626 (46.0); 7,877	33	World Hlth Org Collaborating Ctr Res Human Reprod	170 (85.3); 19
9	Taipei Vet Gen Hosp (TW)	585 (79.0); 1,925	34	China Med Univ (TW)	162 (75.9); 733
10	Natl Hlth Res Inst (TW)	516 (61.8); 2,022	35	China Med Univ	161 (23.6); 2,315
11	Shanghai Jiao Tong Univ	413 (23.0); 3,734	36	Inst Nucl Energy Res (TW)	159 (76.1); 196
12	Second Mil Med Univ	391 (43.5); 2,356	37	SE Univ	144 (47.2); 1,461
13	Chang Gung Med Foundation (TW)	382 (47.4); 7,330	38	Nanchang Univ	134 (31.3); 0
14	Tianjin Med Univ	379 (23.2); 1,172	39	Guangzhou Med Coll	127 (36.2); 294
15	Fourth Mil Med Univ	364 (12.6); 1,562	40	Shaanxi Normal Univ	127 (0.0); 0
16	Nanjing Med Univ	325 (35.4); 1,602	41	Natl Taiwan Univ (TW)	125 (69.6); 624
17	Harbin Med Univ	323 (22.3); 1,939	42	Tri-Serv Gen Hosp (TW)	119 (73.1); 457
18	Nanjing Univ	320 (28.1); 1,833	43	Lanzhou Univ	115 (36.5); 1,457
19	Shandong Univ	303 (41.9); 3,835	44	Hebei Med Univ	112 (8.9); 0
20	Jilin Univ	277 (40.8); 5,249	45	Xi’an Jiao Tong Univ	111 (0.0); 0
21	Soochow Univ	254 (31.9); 1,235	46	Henan Med Univ	110 (33.6); 364
22	China Pharmaceut Univ	249 (23.7); 1,430	47	Peoples Liberat Army 301 Hosp	107 (43.9); 1,513
23	Shanghai Inst Mat Med, Chinese Acad Sci	249 (56.2); 302	48	China Three Gorges Univ	106 (59.4); 0
24	Univ Hong Kong (HK)	247 (65.2); 5,078	49	Tongji Univ	105 (41.0); 808
25	Third Mil Med Univ	227 (40.5); 1,452	50	Xuzhou Med Coll	101 (19.8); 586

*, institutions based in Hong Kong and Taiwan are labelled HK and TW respectively, while others are from the Chinese mainland; WD, weighted degree; LEC, level of external collaborations; BC, betweenness centrality.

Community node-size reflected the degree of a community, and the strength of the edges corresponded to the edge weights measured by the frequency of co-publication between authors in two communities. Moreover, community numbers from 1 to 11 were coded by institution counts in descending order (i.e., the largest community labeled 1 comprised 69 institutions, and the community 11 contained 6 units). Nodal positions in the community network were determined using the Fruchterman-Reingold method.

To gain a thematic analysis of the subnetworks, we counted the appearance of keywords in specific communities and ranked them based on corresponding frequencies. In *Figure 3*, communities are labelled by top keywords, which showed more than 50% cumulative probability in descending order of individual frequency. It is clearly shown that different communities in China’s oncology drug research field shared some common research keywords, such as apoptosis, chemotherapy, cell cycle, breast cancer, lung cancer, gastric cancer, and metastasis. In addition, for absolute frequency of keywords in communities, we used R_{sc} to indicate the relative preferences of communities to specific keywords. Some keywords, whose R_{sc} values are listed in the top 10 positions in specific communities, are shown in bold in *Figure 3* to indicate the leading research

Table 2 Top institutional pairs in Chinese anti-cancer drug research network

Institutional pairs (region)*		Co-publication frequency	Jaccard index (J_{ij})	Geographic adjacency (Y=yes, N=no)**
Natl Yang Ming Univ (Taiwan)	Taipei Vet Gen Hosp (Taiwan)	260	0.361	Y
Chinese Univ Hong Kong (Hong Kong)	Prince Wales Hosp (Hong Kong)	117	0.277	Y
Second Mil Med Univ (Shanghai)	Shanghai Inst Mat Med, Chinese Acad Sci (Shanghai)	94	0.435	Y
Natl Res Inst Family Planning (Beijing)	World Hlth Org CollabCtr Res Human Reprod (Beijing)	67	0.290	Y
China Three Gorges Univ (Hubei)	Yichang Cent Peoples Hosp (Hubei)	51	0.680	Y
Shenzhen Kangzhe Pharmaceut Co., Ltd. (Guangdong)	Tianjin Med Univ (Tianjin)	41	0.402	N
Shanghai Inst Mat Med, Chinese Acad Sci (Shanghai)	Ocean Univ China (Shandong)	36	0.257	N
Hong Kong Univ Sci & Technol (Hong Kong)	CK Life Sci Int Inc (Hong Kong)	24	0.774	Y
Yunnan Univ (Yunnan)	Third Affiliated Hosp Kunming Med Univ (Yunnan)	24	0.522	Y
Nanchang Univ (Jiangxi)	Shaoxing Peoples Hosp (Zhejiang)	22	0.338	Y
Inst Modern Phys, Chinese Acad Sci (Gansu)	Lanzhou Command Ctr Dis Control & Prevent (Gansu)	21	0.778	Y
Hubei Univ Tradit Chinese Med (Hubei)	E China Univ Sci & Technol (Shanghai)	20	0.444	N
Cent S Univ (Hunan)	Shaoxing Peoples Hosp (Zhejiang)	20	0.290	N
China Med Univ (Liaoning)	Liaoning Canc Hosp & Inst (Liaoning)	18	0.474	Y
Guangzhou Med Coll (Guangdong)	So Med Univ (Guangdong)	18	0.346	Y
Huazhong Univ Sci & Technol (Hubei)	Wuhan First Hosp (Hubei)	18	0.257	Y

*, institution's regional location is the provincial-level administrative divisions of China; **, the value of geographic adjacency is "yes" when the institutional partners are located within the same region or physically neighboring regions, on the contrary, the value is "no"

focuses of different network communities. For example, community 1 focused on head and neck cancer, clinical study, liposome, and recurrence, while community 2 led in aspects of peroxisome proliferator-activated receptors, docetaxel, interleukin, and adenovirus.

Moreover, R_{sc} values were used to analyze the effect of research focuses on the position of communities in each research collaboration network. In this research, core subjects on oncology pharmaceutical research in China were defined as keywords with the >5 occurrence frequency in our dataset, whereas the remaining keywords were considered non-core subjects. The whole R_{sc} values of the non-core subjects of different communities were calculated respectively. There was a negative association between the degree of a community in the network illustrated in *Figure 3* and the R_{sc} value of non-core subjects in this community, with a Pearson correlation coefficient of −0.719 ($P<0.05$). This showed that communities focusing on mainstream research subjects were perceived by other communities as highly appealing for research collaboration, whereas communities devoted to rare research had a greater chance of being isolated in a research network, thereby losing collaboration opportunities.

Finally, all of Taiwan's institutions in our dataset assembled in the first community in *Figure 3*. This further supported that geographical proximity determines research collaborations but also that institutions in Taiwan formed a relatively closed society in terms of anti-cancer drug research, wherein members tended to collaborate with one another and block external partners.

Discussion

The focus of this study is on China's organizational

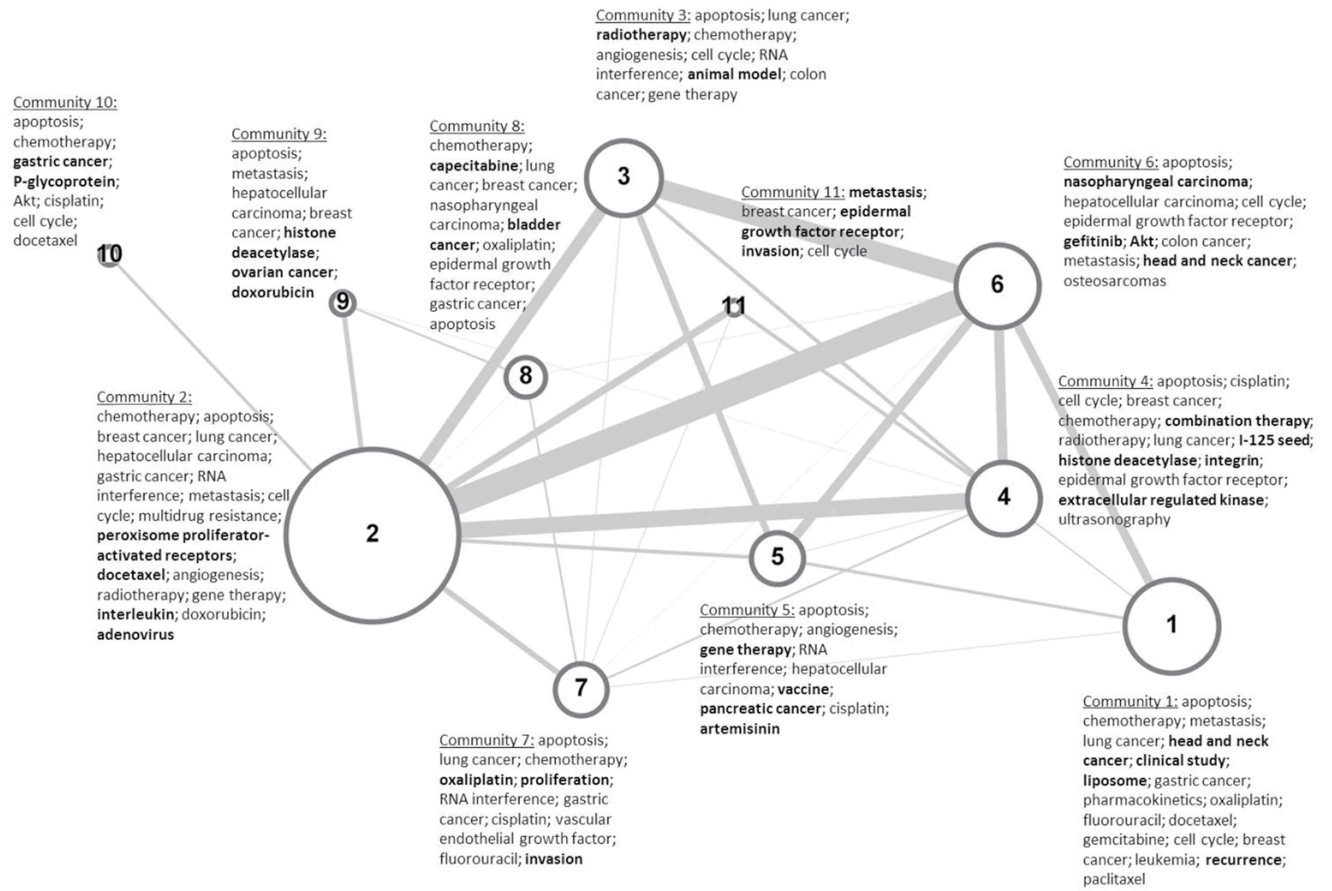

Figure 3 Thematic community network of Chinese institutions on oncology drug research (the supplementary material on member institutions in specific communities is available upon request). This figure is composed of 11 communities which are shown as nodes and labelled by top keywords. Community node-size reflects the number of articles involved in a community, the strength of the edges corresponds to the edge weights measured by the frequency of co-publication between authors in two communities, and numbers from 1 to 11 are coded by institution counts in descending order.

collaboration networks for anti-cancer drug research. It explores the network structures, inter-organizational collaboration patterns and the role of Chinese research units in the network regarding their prominence and prestige as well as regarding their affiliation to a specific network community. The study uses a sample of 675 research articles produced by researcher affiliated to 342 research institutions located in the Chinese mainland, Taiwan, Hong Kong, and Macao.

Interestingly, we find that common interest of two research organizations is the main driver for co-publication activities between them. Therefore, a group of organizations showing a common research interest are likely to form a network community. Such communities have been identified in this study using appropriate community identification algorithms. To characterize the common research interest of a community, we have disclosed the research topics of each identified community by using the distribution of keywords of the articles a community has produced. The keyword labels are diverse and complex, involving cancer types, medicinal chemicals, cellular biology, and molecular biology and so on. Moreover, there are some common high-frequent research keywords across different communities, such as apoptosis, chemotherapy, cell cycle, breast cancer, lung cancer, gastric cancer, and metastasis. The importance of these common research topics is shown in existing literature, for example, some scholars noted that apoptosis and chemotherapy play an important role in carcinogenesis or cancer treatment (21,22), while a study found that breast, lung and gastric cancers cause the most cancer deaths each year in China (23).

The community analysis identifies 11 communities, all of them focusing on distinct research fields, often with a diverse set of expertise fields. Community 1 composed of institutions from Taiwan focuses on head and neck cancer, clinical study, liposome, and recurrence. The institutions within community 2 have tremendous advantage in peroxisome proliferator-activated receptors, docetaxel, interleukin, and adenovirus research; a great number of them are located in the Yangtze River Delta. Organizations in community 3 pay attention to radiotherapy and animal model, mostly concentrated in Southwest China. Community 4 taking Beijing organizations as leaders is concentrated on combination therapy, I-125 seed, histone deacetylase, integrin, and extracellular regulated kinase. Most of Hong Kong institutions are included in community 6 which is focusing on nasopharyngeal carcinoma, gefitinib, Akt and head and neck cancer.

It is worth noting that cross-community collaboration opportunities are negatively associated with the degree of specialization of a community. In other words, hot research areas attract more attention and cooperation; on the contrary, less cooperation exists in specialized research areas. Therefore, common interest as main basis for cooperation should be the point of reference for policy makers in the development of R&D projects. Further, future developments and discoveries in pharmaceuticals must be taken into account by policy makers, as they may lead to dynamic re-organization of the network to account for changing research interests.

On the other hand, from a systemic innovation perspective, innovation most strongly emerges in the cooperation process between organizations (24,25) that are complementary regarding their knowledge base. These results are of great significance to recommend some policies for stimulating research cooperation. For example, in this present work, regional pairs show that most solid partner relations have relatively equal research capabilities. In this sense, to close the gap between regional science and technology development, cross-regional cooperation between developed and less developed regions should be included in policy structure to stimulate balanced development of science and technology in the Chinese mainland.

Moreover, we draw some significant conclusions from the centrality analysis of participating organizations in the network. Concerning R&D investment policies, the organizations with high betweenness centrality should focus more on outreach to other institutions. For instance, Peking University, Huazhong University of Science & Technology, Sichuan University, and Jilin University are dispersed across the Chinese territory. As the network gatekeepers and brokers, these institutions can have more positive impacts on knowledge diffusion and research collaborations. More importantly, they play the key role for enhancing R&D efficiency within the whole network. Increasing R&D investment into these institutions could significantly stimulate R&D collaboration and promote resource sharing and knowledge diffusion. Additionally, it is worth noting that Hong Kong plays an important role in the whole network in terms of a brokerage function between the Chinese mainland and Taiwan.

There are also limitations in this study. First, the sample may be extended to a larger number of articles and co-publications. In this context, the robustness of the results from the community analysis could be tested using methods to identify hierarchies of communities. Second, the analysis may be expanded to account for temporal properties of the network in further research. In light of the increasing number of publications from China concerning oncology, such an analysis is expected both to be feasible and necessary. Finally, the study is limited to the academic sphere in using academic publications, and, in this sense, mainly focuses on basic research. Though basic research constitutes the fundament for innovation, a similar exercise for applied and competitive research would be an important addition to the current study, for instance by focusing on collaboration in patenting or licensing.

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