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Article

Collaboration in science and technology organizations of the public sector: A network perspective

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Abstract

Engaging in collaborative networks can be an important facilitator of innovation for public sector science and technology (S&T) organizations. It is also an important component of S&T policies that require indicators that can assess the networks through which these organizations innovate. In this study, we apply network indicators to two S&T organizations that are part of the Brazilian public health sector. The indicators cover two complementary perspectives: one that considers the organizations' scientific networks and the other that considers their technological networks. The indicators allowed the analysis of the networks in which the organizations were engaged and the understanding of important aspects of their collaboration patterns that can support strategic decisions. The method employed in this paper proved to be a valuable diagnostic tool and a useful mechanism for evaluating the performance and supporting the development of S&T institutions.

Key words: networks; collaboration; R&D; public sector; indicators; Brazil.

1. Introduction

Engaging in collaborative networks can be an important facilitator of innovation processes in science and technology (S&T) organizations, for both academia and industry. When collaborating, researchers can establish communication networks, share ideas, resources and information, generate new knowledge and ultimately create innovations, thus reducing the costs and increasing the productivity of research (Wagner and Leydesdorff 2005). In industry, especially in high-tech fields, networks provide access to the knowledge and other resources that are necessary for the successful development of new products (Haeussler et al. 2012) and to enhance the innovation output and competitiveness of organizations (Baum et al. 2000).

Networking has had a positive and significant impact on how public problems are addressed by public sector organizations (Bommert 2010). Particularly in the health sector, networks are seen as means to tackle complex problems, which usually require transdisciplinary and multidisciplinary teams to understand and address their complexity (Leischow et al. 2008). Several authors have emphasized the significance of multi-organizational partnerships for promoting innovations in health (Mays and Scutchfield 2010), whether to develop products for the needs of less developed countries (Morel et al. 2005) or to provide quality products and therapies to healthcare systems (Melese et al. 2009). In developing countries, where most of the infrastructure for health research is in the public sector, technological innovation through the partnering of S&T organizations is as a method to improve and establish regional and international networks that could link the knowledge generated by these organizations to productive units (Morel et al. 2005). The notion of networks has turned into an important component of scientific–technological complexes and has become an instrument of S&T policies (Royal Society 2011).

The current innovation models require indicators that can account for the nonlinearity of the innovative process and the connection of innovators to the external and internal environment, including metrics to assess the collaborative networks through which an organization innovates (Gamal 2011). Therefore, the evaluation of the collaborative networks to which S&T organizations belong is of the utmost importance. In this study, we assume that engaging in collaborative networks provides an important advantage for S&T organizations in the public sector. We expand the knowledge about collaborative networks for research and technological development by selecting a set of indicators and applying them to two S&T organizations that are part of the Brazilian public health sector (Bio-Manguinhos (B-M) and the Butantan Institute (BI)).

The indicators cover two complementary perspectives: one that addresses the organization's scientific networks, by means of the co-authorship of scientific papers, and other that approaches its technological networks, which evaluates the co-inventorship of patents. Both address the organization as a whole and its relations with other institutions, as well as the individual relationships and the power structure of the central and peripheral actors within the organization. Thus, one can obtain information about the level of collaboration of the organization, map its strategic alliances, and also identify the characteristics of its individual members, to reveal where interventions are needed.

The remainder of this paper is organized as follows: Section 2 presents the theoretical background for the selection and use of the indicators, with an emphasis on co-authorship and co-inventorship network metrics and their use as indicators of collaboration. Section 3 presents the method used to produce the indicators and provides a brief presentation of the organizations to which they were applied. The results generated by the indicators are described in Section 4. Section 5 discusses the results and Section 6 concludes the paper.

2. Theoretical background

2.1 Collaboration in S&T organizations

Collaboration is a hallmark of S&T institutions and engagement in networks has become the most important organizational innovation associated with the spread of the knowledge economy. The competitiveness of S&T organizations is related to the scope of the networks in which they operate, as well as to the intensity of their use (Zaheer et al. 2010).

In S&T organizations, collaboration networks act to: provide a knowledge-sharing environment (Wagner and Leydesdorff 2005), broaden the scope of projects (Beaver 2001), and improve research impact (Royal Society 2011). Beyond the benefits seen in research environments, networks for technological development can also leverage knowledge creation and innovation. The competences and capabilities that are necessary to transform a scientific discovery into a product are distributed among various organizations (Powell 2002) and there is an increasing demand for inter-functional and inter-institutional cooperation, particularly in areas with a high-tech content (Ramesh and Tiwana 1999), such as the health sector.

Several studies have shown the increasing scale and importance of collaboration networks and several institutions have adopted a network perspective, by analyzing co-authorship and co-inventorship networks, to understand and evaluate collaborations, as well as to identify the important players in these networks (Royal Society 2011; Netherlands Observatory of Science and Technology 2010; Marsan and Primi 2012).

2.2 Co-authorship and co-inventorship networks

It has long been realized that the co-authorship of scientific papers and the co-inventorship of patents are powerful instruments for analyzing scientific and technological collaborations and partnerships, providing a window onto patterns of cooperation among individuals and organizations (Balconi et al. 2004; Ozcan and Islam 2014; Lee et al. 2012). Co-authorship and co-inventorship networks can document collaborations between two or more actors. In these networks, collaboration is depicted in such a way that actors represent authors or inventors, and two or more actors are connected by a line if they have worked together as authors/inventors of one or more papers/patents (Newman 2004). Inter-institutional cooperation can be defined in terms of papers/patents co-signed by authors/inventors from two or more institutions.

Previous studies have suggested the use of co-authorship networks as tools to evaluate government-funded programs (Yang and Heo 2014), for public policy planning and promotion of innovation management in public health systems (Morel et al. 2009; Vasconcellos and Morel 2012), for competitive intelligence in organizations (Alcará et al. 2006) and also to support communicative management networks for health innovation systems (Martins et al. 2012). Co-inventorship networks have been used to analyze the structure of R&D collaboration among organizations and their innovative outcomes (Guler and Nerkar 2012), the relationships between inventors in several research fields (Ozcan and Islam 2014), and also the quality of patents (Beaudry and Schiffauerova 2011).

These networks reveal important features of an organization. The publication of a scientific paper can be thought of as a process directed at understanding a determined phenomenon, manifesting an official relationship and involving two or more authors or institutions (Glänzel and Schubert 2005). Filing a patent application can be viewed as an activity which: aims to create products, functions as an intermediate output indicator for innovation activity and provides information on the organization's innovative capabilities (Organisation for Economic Co-operation and Development 2005).

2.3 Co-authorship and co-inventorship network metrics

Quantitative metrics in co-authorship and co-inventorship networks may reflect the properties of the network as a whole or those of its individual nodes. The network-level metrics provide information about its structural properties and the individual-level metrics provide information about the position of each actor in the network, according to the relations that actor maintains. The indicators used in this study included both perspectives. For the network-level metrics we focused on the number of actors (nodes) and links, the density, average degree, average path length and modularity of the network, and the number of existing communities. For the individual-level metrics we considered the degree and betweeness centrality of the nodes.

The number of nodes and links represent the size of the network, reflecting the number of nodes involved in the network and the number of connections between them, established in accordance with their relational attributes. The network density is a metric designed to measure the connectivity within the network and is defined as the percentage of the number of existing links (real) and the maximum number of possible links in a given network (Wasserman and Faust 1994). Thus, dense networks are those in which there are many connections, with density values close to one, and sparse networks are those that have few links, with density values close to zero. The average path length is the average shortest path between any two nodes in a network, that is, the average number of 'steps' necessary to move from one node to another (Scott 2001). The average degree represents the average number of connections that the nodes of a given network have. The community structure is the division of a network into groups or modules whose internal connections are dense and whose external connections are sparse (Newman 2012). In this study, community detection was based on the concept of modularity, used to identify denser subsets within a network. According to this concept, these subsets can be considered to be a community if the number of internal connections within them is denser than the expected number of connections between these nodes and the rest of the network (Newman 2012).

The centrality measures describe the importance of a node relative to all other nodes in a given network. These measures take account of the different ways in which a node interacts and communicates with the rest of the network. The most important, or central, ones have a strategic significance in the network. The degree centrality can be defined as the number of links that a node has with other nodes. The more relational ties a node has, the more power or prestige it may have in a network. The betweeness centrality is based on the extent to which a particular node lies between other pairs of nodes in a network, connecting them (Freeman 1979). Nodes that are often on the shortest path between other nodes are deemed to be highly central because they control the flow of information in the network by connecting different groups.

2.4 Network metrics as indicators of collaboration

Despite being widely used to understand and evaluate patterns of collaboration, studies that associate co-authorship and co-inventorship network metrics with an indicator perspective are still emerging. Network metrics have been used to evaluate the influence of the position of Canadian inventors on the quality of their patents in nanotechnology (Beaudry and Schiffauerova 2011), to identify the most prominent researchers and countries and the formation of research groups in leishmaniasis research (Gonzalez-Alcaide et al. 2013), to study the impact of collaboration on the performance of Korean public research institutions (Lee et al. 2012), to characterize the social capital of information systems researchers and its influence on the impact of their research (Li et al. 2013), and also to evaluate the technological knowledge flow between countries, institutions and research areas in the field of organic photovoltaic cells (Choe et al. 2013). World-renowned organizations, such as the Royal Society, the Organisation for Economic Co-operation and Development and the Inter-American Development Bank, have also taken advantage of co-authorship and co-inventorship network metrics to account for cooperation and knowledge transfer processes (Royal Society 2011; Netherlands Observatory of Science and Technology 2010; Marsan and Primi 2012; Giuliani and Pietrobelli 2011).

Most of these indicators focus on the analysis of research areas and technological fields, in order to make national and international comparisons. None of them use network metrics as an organizational intelligence tool to provide strategic information about a single organization. Therefore, this study is not designed to evaluate entire research/innovation systems, but rather to examine the underlying network structure that describes the cooperative relations, both internal and external, of S&T organizations in the public sector. By analyzing the networks in which they are included, these organizations can: gain knowledge about their own collaboration patterns, identify key individuals, promote interventions, obtain information to support strategic planning and decision-making processes, and ultimately formulate institutional policies.

3. Data and methodological approach

This study explores co-authorship and co-inventorship network metrics as the basis for the selection and usage of indicators to examine the research and technological development relationships and the collaborative interactions of S&T organizations in the public sector. Two indicators were used: Indicator 1, named 'structured collaboration for the advancement of scientific knowledge', was focused on the co-occurrence of authors or organizations in published scientific papers. Indicator 2, named 'structured collaboration for technological development and innovation', was based on the co-occurrence of inventors and their affiliated organizations in filed/granted patents.

3.1 Brief characterization of the organizations evaluated

Bio-Manguinhos (B-M) and the BI are government-owned laboratories in Brazil that produce and develop immunobiological and biopharmacological products. Together, they provide 80% of the nationally produced vaccines/serums that are distributed to Brazil's entire population and have strategic importance for the Brazilian health–industrial complex (Franco and Kalil 2014). Their value relies on three different dimensions: the social dimension, because their products directly reflect on the welfare of the population; the technological dimension, by promoting a reduction in the technological gap for emerging/neglected diseases where the private sector is not present; and the economic dimension, as they pursue the reduction of the balance of trade deficit through the substitution of imports and the generation of highly skilled jobs. Nevertheless, these organizations have limited competitive ability, either because of their dependence on the market, or because they adopt management practices that are not appropriate to the competition standards of the sector.

B-M is part of the Oswaldo Cruz Foundation (Fiocruz), an S&T organization of the Brazilian Ministry of Health and one of the most prominent public health institutions in Latin America. It occupies a prominent position in the country, participating in public policies for prevention, diagnosis and treatment of diseases by producing biopharmaceutical products, diagnostic reagents and vaccines. B-M was founded in 1976 with the initial goal of reducing Brazil's dependence on products manufactured abroad. In recent years, its growth trend has been marked by the strengthening of technological development and innovation activities such as: the incorporation of new production technologies, continuous modernization of the technological and industrial park located on the Fiocruz campus, and the introduction of new products which have a significant impact on public health. Data from 2014 show that B-M employs 1,592 people, 72 of them with doctorates and 198 with master's degrees. Its technological development area has 150 employees and is focused not only on solutions for problems arising from the production area, but also on projects which aim to improve existing products, the development of new products and the implementation of platforms. In 2014, approximately U$29.7 million was invested in R&D, corresponding to 4.34% of the institute's total revenue.

The BI, one of Brazil's most prestigious scientific institutions, is linked to the Secretary of Health of São Paulo State. It generates new knowledge through scientific research, develops and produces immunobiological and biopharmacological products of interest to public health, educates and trains human resources in the S&T area, and seeks to stimulate and disseminate scientific knowledge among the general population. It was founded in 1901 with the immediate responsibility of producing a serum to be used in the bubonic plague epidemic which afflicted Brazil at that time. Since then the BI has continued its work in many different areas, becoming known as an important producer of several anti-ophidic serums and a groundbreaking scientific institute. It employs about 700 people, including 191 researchers, and has over 420 students in master's, doctoral and postdoctoral positions. The research conducted at the BI is funded by grants from federal and state agencies and provides support for all of its products, both in use and under development, ensuring that the processes and new products can incorporate the knowledge appropriate to the rapid advances in immunobiology.

The decision to analyze these two S&T organizations was based on the fact that both B-M and the BI represent relevant and rich initiatives to consider collaboration as a way to overcome or mitigate barriers to technological strategies in less developed countries. We believe that the analysis of these organizations provides critical reference points for reflection on the scientific and technological development in biotechnology made by the public sector in Brazil, as well as on the role of cooperation as a response to the challenge of building local technological capacity as a basic source of competitiveness and development in health.

It should also be noted that, although two case studies of S&T organizations are presented here, this is not a comparative study. Our main goal is to explore the information that can be unraveled using network indicators in an organizational analysis. Even though B-M and the BI undertake similar activities, each has its idiosyncrasies and should therefore be evaluated in the light of its performance contexts, habits, practices, organizational and innovation cultures etc. That is beyond the scope of the present study.

3.2 Data collection

In order to evaluate patterns of cooperation at B-M and the BI, the data mining strategy was based on retrieving papers and patents that had at least one author/inventor affiliated to these organizations. Therefore the author and inventor sample consists of at least one author/inventor reporting B-M or the BI as their organizational affiliation as well as their collaborators, irrespective of their affiliation.

Examining the network topologies and characteristics for a given organization requires a dataset capable of characterizing its members. This study uses data from two different databases: the publication data was obtained from the Web of Science (WoS) database, maintained by Thomson Reuters, and the patent data was retrieved from the Worldwide Database from the European Patent Office (Espacenet).

In the WoS database, queries were made in the 'basic search' mode directed at the addresses of the authors to retrieve papers (articles, articles in press and reviews) with at least one author from B-M or the BI. In the Espacenet database, the query was directed towards the applicant's name. The search for B-M used 'Fundação Oswaldo Cruz' as the search word. This approach was taken because specifically for patent-related issues, all patents are assigned to Fiocruz, its parent organization. The search retrieved 139 results that were filtered according to information on inventor names retrieved from the Technological Innovation Nucleus of the institution in order to identify patents by B-M inventors. Patents that had been granted, as well as patent applications, were considered for analysis and there were no filters on the classes of the patents. Search parameters included patents filed in Brazil and abroad.

In order to evaluate the individual and institutional levels, we took advantage of two different approaches that differ from each other in the time periods that they evaluate. To assess the formation and eventual growth of cooperation among individuals in the organization, the evolution of the co-authorship and co-inventorship networks was followed using a five-year moving window, which has been widely adopted elsewhere (He and Fallah 2009; Eslami et al. 2013). We also took advantage of the historical outlook of the individual and institutional collaborations. Thus, the analysis also concerned cumulative networks that span a 15-year period. This cumulative approach has also been taken by studies that have addressed co-authorship/co-inventorship analysis in organizations (Li et al. 2013; Ter Wal 2013), including papers that evaluate these networks in Brazil (Morel et al. 2009; Vasconcellos and Morel 2012).

Hence, the five-year networks could be considered more as an approximation of the structure of the existing cooperation at the time it was evaluated. The cumulative networks are more an indication of the ever growing underlying social network that potentially functions as a network through which relevant innovation-related knowledge can persist (Breschi and Lissoni 2005). This study considered the period 1999–2013.

It should be noted that publications with a hundred or more authors were excluded from the analysis. This methodological choice was taken because we understood that, in such articles, co-authoring is not due to collaboration, but mostly to the independent contributions to joint efforts, usually in the form of data, involving only weak intellectual interactions (Adams 2012).

3.3 Standardization of names and addresses of authors and institutions

A process of standardization was carefully carried out to bring together the various names of a particular author or institution. This process of disambiguation is extremely important in order to attribute a paper/patent to the correct author once the record has been retrieved. The publication data was processed using the VantagePoint software (Search Technology Inc.), with specific filters for the WoS database. The patent data was processed manually.

As we were interested in both individual and institutional levels of analysis, affiliation data was extremely important for our research. For the publication data, the affiliation of the authors was obtained directly from the WoS database. For the patents data, information on the affiliation of Brazilian inventors was obtained from the Lattes Platform, an information system maintained by the Brazilian government to manage information on individual researchers. The affiliation of international inventors who were not included in the Lattes Platform was obtained through research on the World Wide Web. In this process, the authors/inventors who had no affiliation data were excluded from the analysis.

3.4 Network assembly, visualization and analysis

After treatment and processing, data retrieved from patent and publication databases were translated into adjacency matrixes to generate authors $\times$ authors networks and institutions $\times$ institutions networks. The open-source software Gephi (Bastian et al. 2009) was used to visualize the network graphs and perform the statistical analysis. As collaboration presupposes reciprocity among participants, all links between nodes were considered to be undirected.

4. Results

4.1 Publication and patent records

The search for data on scientific publications and patents from B-M retrieved 131 and 13 records, respectively. The search for data from the BI retrieved 2,109 scientific publications and 21 patents. Fig. 1 shows the evolution of the number of published papers and patents for each organization per year.

The five most frequent keywords in B-M publications ('vaccine', 'yellow fever', 'yellow fever vaccine', 'cytokines' and 'attenuation') reflect the fact that vaccines are its main research topic. The five

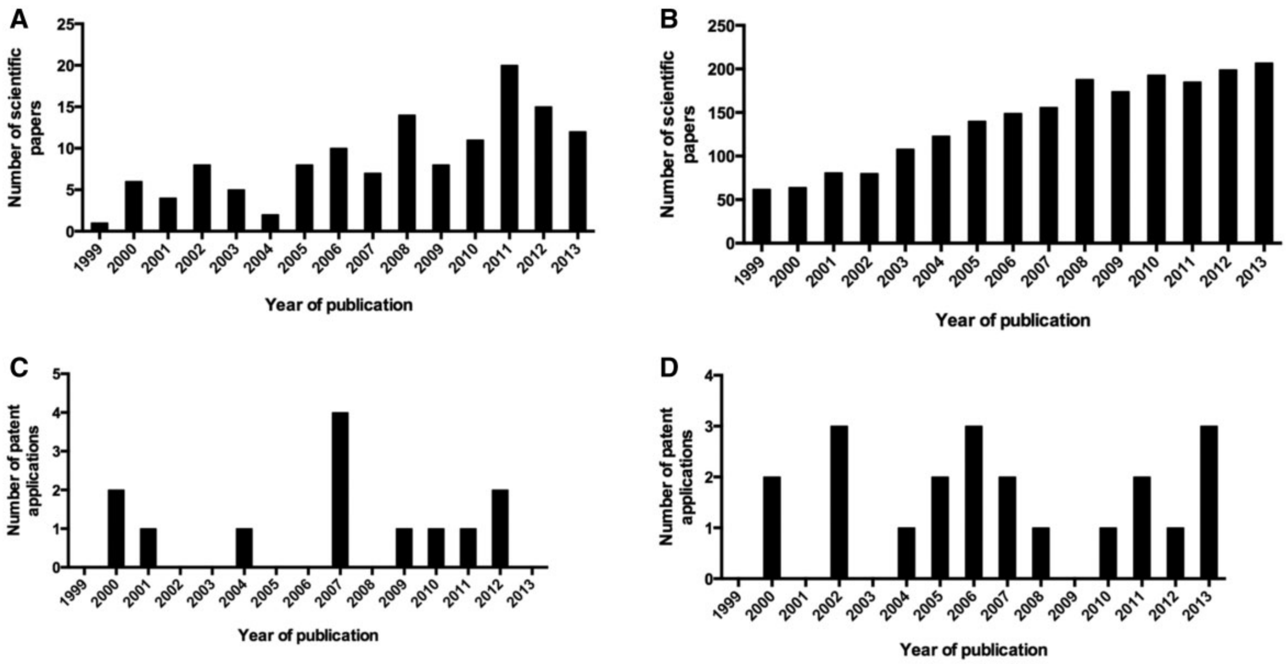

Figure 1. Yearly evolution of the number of scientific papers and patent applications from B-M (A and C) and the BI (B and D)

A and B: Number of scientific papers published per year, in period 1999–2013 from B-M (A) and the BI (B)

C and D: Number of patent applications published per year, in period 1999–2013 from B-M (C) and the BI (D)

It should be noted that the publication date of a patent is the date on which a patent application is first published. It is the date on which the document is made available to the public, thereby making it part of the state-of-the-art.

Table 1. Metrics of scientific publication networks at B-M and BI: Individuals

	Bio-Manguinhos			Butantan Institute		
	1999–2003	2004–2008	2009–2013	1999–2003	2004–2008	2009–2013
Number of nodes (authors)	133	223	396	1,270	2,333	3,071
Number of links	669	1,261	2,970	9,740	18,094	19,173
Average degree	10.6	11.3	15	15.3	15.5	12.4
Average path length	2.57	3.63	3.26	3.94	4.13	4.3
Modularity	0.65	0.76	0.78	0.77	0.80	0.84
Number of communities	7	7	20	34	32	41
Density	0.076	0.051	0.038	0.012	0.007	0.004

most frequent keywords in the BI publications are ‘taxonomy’, ‘Brazil’, ‘snake venom’, ‘inflammation’ and ‘vaccine’, demonstrating the direct relation of the research conducted at that institute with the diversity of animals in Brazil, especially venomous animals.

An analysis of the International Patent Classification codes in which B-M and the BI patents were included shows that both organizations act, and have competences, in the biotechnology area. The A61K39 code is the most frequent, present in 71% and 75% of the patents of the BI and B-M, respectively. This class includes preparations for medical purposes, specifically medicinal preparations containing antigens or antibodies.

4.2 Indicator 1: Structured collaboration for the advancement of scientific knowledge

Individual and institutional co-authorship networks were constructed in order to depict the structure of B-M and the BI collaboration in scientific papers and reconstruct the networks in which their authors have been involved. The evolution of the individual co-authorship networks of both organizations was studied in five-year periods, spanning the period 1999–2013. Their principal metrics are shown in Table 1.

It can be seen that the number of authors involved in the scientific networks of B-M grew approximately 67% in the first five years and 77% in the second five-year period. The same indicator applied to the BI also shows a growth, which was stronger in the first five years (83%) and slightly lower in the second five years (31%). At B-M, the average degree of the network increases slightly over time, suggesting a rise in collaboration within the network. Conversely, in the BI, the average degree remains practically the same in the first five years and decreases in the last period that was evaluated. Despite this, the average path length, the number of communities and the modularity values have increased, indicating that the network has become more fragmented over time. In the most recent

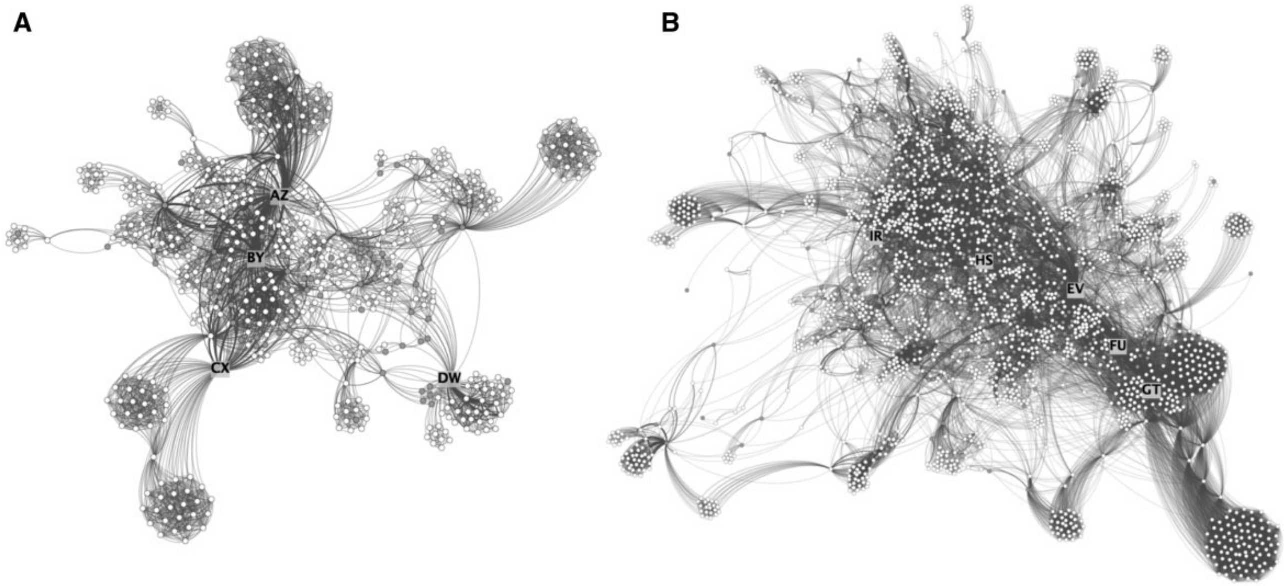

Figure 2. Individual co-authorship network of B-M (A) and the BI (B), in period 1999–2013

Relations between two researchers were mapped according to their co-authorship in scientific papers. Each node is an author and two authors were considered connected if they shared the authorship of a paper

The thickness of links indicates the frequency of collaboration between two nodes. The node color indicates whether the author is from B-M (A = gray) or the BI (B = gray) or from other institutions (white)

For ease of visualization, only authors in the BI network that have collaborated in 10 or more papers were shown (n = 2,459)

The name of the most important researchers in each network is also indicated. Only the largest component is shown for both networks

Table 2. Ranking of three most important authors at B-M and BI, based on network centrality measures

	Rank	Author	Degree centrality	Author	Betweeness centrality
Bio-Manguinhos	1	AZ	0.237	BY	0.207
	2	BY	0.208	AZ	0.193
	3	CX	0.122	DW	0.139
Butantan Institute	1	EV	0.081	EV	0.113
	2	FU	0.058	HS	0.054
	3	GT	0.056	IR	0.053

time period, the density values show that only 3.8% and 0.4% of all possible connections are being effectively utilized in the B-M and BI networks, respectively.

To evaluate the most important and central researchers in the networks of scientific publications of B-M and the BI, two centrality measures were analyzed: degree centrality and betweeness centrality. In order to gain a historical perspective, for this analysis we took advantage of a cumulative network that spans the entire 15-year period under investigation (see Fig. 2). The individual co-authorship network at B-M includes 105 of its researchers among 640 nodes (see Fig. 2A). The BI network consists of 5,267 nodes, including 437 researchers from this organization (see Fig. 2B). Table 2 shows the principal researchers of both organizations, according to the centrality measures evaluated. Centrality values were normalized according to the size of the network. In B-M, AZ, BY, CX and DW are more central and in the BI, this role is played by EV, FU, GT, HS and IR.

To reflect the institutional pattern of collaboration in scientific publications at B-M and at the BI, institutional co-authorship networks were built based on all records retrieved (period 1999–2013) (see Fig. 3). The B-M network (see Fig. 3A) has 128 nodes, with international institutions participating in 56.7% of collaborations and Brazilian institutions included in 43.3% of collaborations. The BI network (see Fig. 3B) consists of 692 nodes, with international institutions participating in 62.4% of collaborations and Brazilian institutions included in 37.6% of them.

Their evolution, which was studied in five-year periods (see Table 3), shows a growth in the number of participating institutions in both B-M and the BI. At B-M there was a mild increase in the first five-year period (15%) but a marked increase (147%) in the last five years that were evaluated. In the BI, the opposite occurred: a more pronounced growth in the first five years (75%) and a slight increase (18%) in the last period that was evaluated.

Historically, B-M's main collaborators are other Fiocruz units, especially Fiocruz-RJ (Fio-RJ), with a total of 79 of 102 articles in co-authorship, and the Federal University of Rio de Janeiro, with 16 co-authored publications. In the case of the BI, its most frequent collaborators are the University of São Paulo (USP) and the Federal University of São Paulo (UNIFESP), with a total of 912 and 237

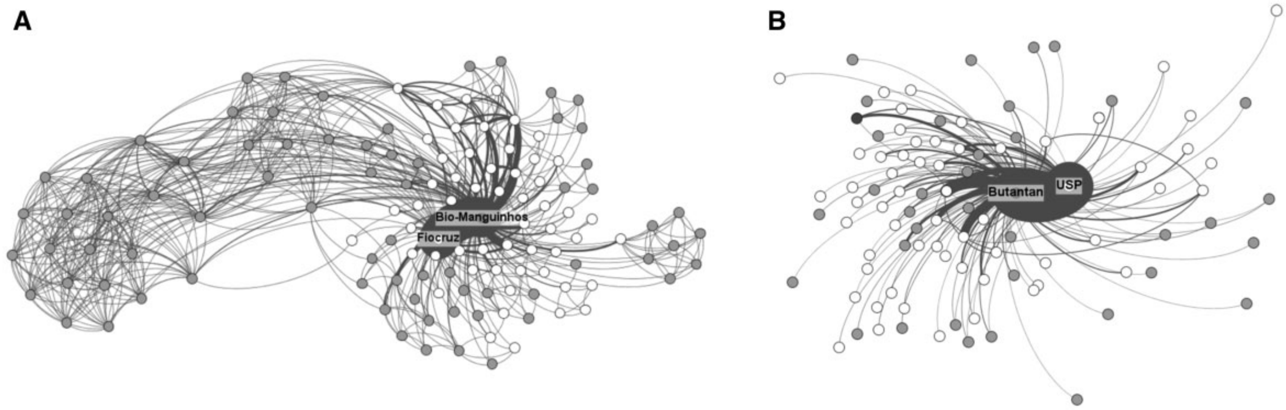

Figure 3. Institutional co-authorship network of B-M (A) and the BI (B), in period 1999–2013

Relations between two institutions were mapped according to the affiliations of the authors of scientific papers. Each node is an institution and two institutions were considered connected if its members shared the authorship of a paper

The thickness of links indicates the frequency of collaboration between two nodes. The node color indicates whether the institution is Brazilian (white) or international (gray)

B-M (A) and the BI (B) are represented in the center of their respective networks

For ease of visualization, in the BI network only institutions that have collaborated in five or more papers were shown (n = 150)

The name of their most frequent collaborator is also indicated

Table 3. Data of scientific publication networks at B-M and BI: Institutions

	Bio-Manguinhos			Butantan Institute		
	1999–2003	2004–2008	2009–2013	1999–2003	2004–2008	2009–2013
Number of nodes (institutions)	33	38	94	213	374	442
Number of links	95	93	569	829	1655	2136
Most frequent collaborators(*)	Fio-RJ (15) UFF (5) USP (3)	Fio-RJ (23) UFRJ (7) Fio-PE (3) Fio-MG (3) Fio-BA (3)	Fio-RJ (41) UFRJ (7) Fio-MG (6)	USP (149) UNIFESP (46) UNESP (33)	USP (327) UNIFESP (73) UNESP (63)	USP (433) UNIFESP (116) UNESP (67)

*number of co-authored publications
Fio-BA = Fiocruz-Bahia
Fio-MG = Fiocruz-Minas Gerais
Fio-PE = Fiocruz-Pernambuco
Fio-RJ = Fiocruz-Rio de Janeiro
UFF = Federal Fluminense University
UFRJ = Federal University of Rio de Janeiro
UNESP = São Paulo State University
UNIFESP = Federal University of São Paulo
USP = University of São Paulo

co-authored articles, respectively. In both organizations most collaboration takes place in the university sector (40–48%), but a lot of interaction also involves research institutes (14–19%). In the BI the same three institutions (USP, UNIFESP and the São Paulo State University) collaborate more intensively with the organization throughout the entire period evaluated (see Table 3).

4.3 Indicator 2: Structured collaboration for technological development and innovation

Individual and institutional co-inventorship networks were constructed in order to represent the structure of the collaboration in patents and reconstruct the networks in which inventors from B-M and the BI have been involved. As in the previous analysis of the scientific networks, the evolution of the individual co-inventorship networks of both organizations was studied in five-year periods, over the time span 1999–2013. The principal metrics are shown in Table 4.

The analysis of these co-inventorship networks shows a growth in the number of participating individuals and in the size of the networks over the period analyzed, evidenced by the increase in the number of nodes and links. The co-inventorship network has increased by 155% at B-M and by 150% at the BI. This growth in size was accompanied by an increase in collaboration, shown by a significant rise in the average degree of the network when comparing the first and last periods being evaluated.

Table 4. Metrics of patent networks at B-M and BI: Individuals

	Bio-Manguinhos			Butantan Institute		
	1999–2003	2004–2008	2009–2013	1999–2003	2004–2008	2009–2013
Number of nodes (inventors)	9	23	29	14	35	48
Number of links	16	62	129	23	152	203
Average degree	3.5	5.7	8.8	1.1	8.4	8.4
Average path length	1	1	1.23	3.28	2.17	2.13
Modularity	0.48	0.61	0.31	0.63	0.51	0.64
Number of communities	2	4	3	4	5	5
Density	0.44	0.24	0.31	0.25	0.25	0.18

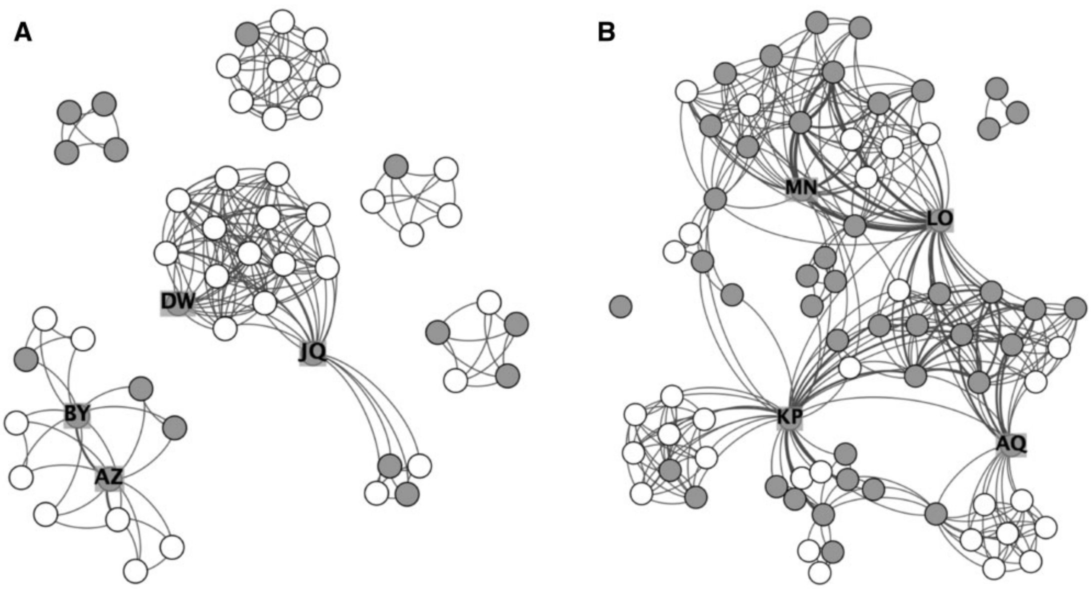

Figure 4. Individual co-inventorship network of B-M (A) and the BI (B) in period 1999–2013

Relations between two inventors were mapped according to their co-inventorship in a patent document. Each node is an inventor and two inventors were considered connected if they shared a patent

The thickness of links indicates the frequency of collaboration between two nodes. The node color indicates whether the inventor is from B-M (A = gray) or the BI (B = gray) or from other institutions (white)

The names of the most important inventors in each network are indicated

Table 5. Ranking of three most important inventors at B-M and BI, based on network centrality measures

	Rank	Author	Degree centrality	Author	Betweeness centrality
Bio-Manguinhos	**1**	JQ	0.333	JQ	0.039
	2	DW	0.259	BY	0.023
	3	BY	0.185	AZ	0.013
Butantan Institute	**1**	KP	0.480	KP	0.486
	2	LO	0.441	LO	0.222
	3	MN	0.298	AQ	0.181

In order to identify the most important inventors, we took a historical perspective of the co-inventorship networks, represented by the cumulative collaboration network for the period 1999–2013 (see Fig. 4). The B-M individual co-inventorship network includes 18 of its inventors among 55 nodes (see Fig. 4A). The BI network consists of 77 nodes, including 47 inventors from this organization (see Fig. 4B). Table 5 shows the most central inventors of both organizations. Centrality values were normalized in accordance with the size of the networks. At B-M, the most important inventors are JQ, DW, BY and AZ. KP, LO, MN and AQ are the most central at the BI.

In order to identify and map the organizational partners of B-M and the BI, the co-inventorship networks were also analyzed at the institutional level (see Fig. 5). The B-M network (see Fig. 5A)

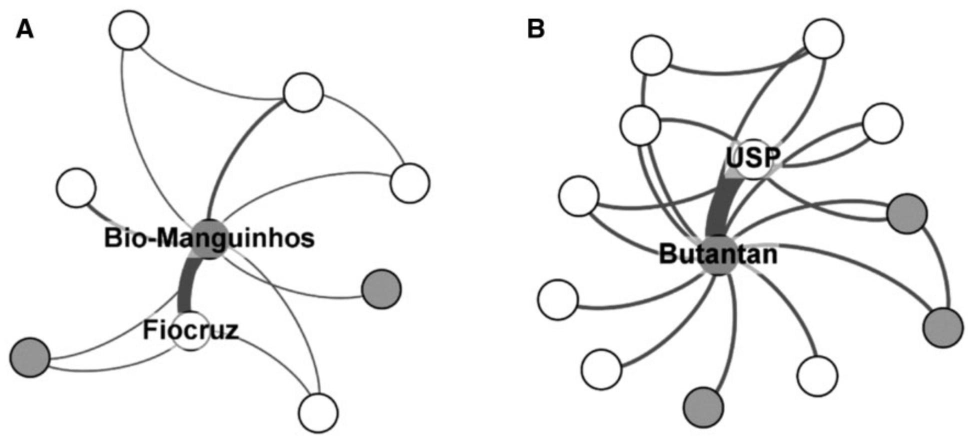

Figure 5. Institutional co-inventorship network of B-M (A) and BI (B): 1999–2013

Relations between two institutions were mapped according to the affiliations of the inventors in patent documents. Each node is an institution and two institutions were considered connected if its members shared the inventorship of a patent

The thickness of links indicates the frequency of collaboration between two nodes. The node color indicates whether the institution is Brazilian (white) or international (gray)

B-M (A) and the BI (B) are represented in the center of their respective networks

The name of their most frequent collaborator is also indicated

includes eight partners and national organizations play a leading role in partnerships with 85% of all cooperations. In the BI network (see Fig. 5B), 12 partner institutions are present and national organizations participate in 87.5% of all collaborations.

Their evolution, studied in five-year periods, (see Table 6) shows a growth in the number of participating institutions at both B-M and the BI. At B-M there was a modest increase in the first five-year period (15%) but a marked increase (147%) in the last five years that were evaluated. The opposite occurred at the BI: a more pronounced growth in the first five years (75%) and a slight increase (18%) in the last five years that were evaluated.

Historically, a Fiocruz unit (Fio-RJ) is the most frequent partner of B-M, cooperating in about 46.6% of all patents. The USP is the major collaborator with the BI in the development of patents, being involved in approximately 31.2% of all patents filed by that institute. In both organizations, most collaborations are with the university sector (50–58%). At B-M, a lot of interaction also involves research institutes (37.5%). At the BI, hospitals and medical centers are also important collaborators (25%). No private companies were identified as part of the networks.

Table 6 also shows that both organizations tend to cooperate with different institutions in each period, rather than collaborating with the same ones throughout the entire period (1999–2013).

5. Discussion

This study was based on the premise that participating in networks is an important advantage for the performance of public sector S&T organizations. Engaging in collaborative networks results in a greater impact for their research (Royal Society 2011) and, even outside academic borders, industrial organizations that are involved in networks are more innovative than those who do not participate in such settings (Schilling and Phelps 2007). Since scientific research and the development of innovations are increasingly multidisciplinary and complex, especially in the health area, entering in cooperative networks is essential for organizational success.

The data that was collected showed a marked difference in the numbers of scientific papers published by B-M and the BI. This may be related to the orientation adopted by B-M, which compared to the BI, gives greater weight to industrial production activities, subordinating the application of research results to industrial matters (Gadelha and Azevedo 2003). This greater emphasis on industrial activities may have influenced the number of employees involved in R&D activities and inhibited the publication of scientific papers focused on academic purposes. In contrast, the mission of the BI covers research and knowledge sharing with society, encouraging the publication of scientific papers by its members.

Public sector organizations consider patenting to be a way of ensuring access to technologies/products for the population and preventing the imposition of unfair conditions that could hinder this access. Even if the organization does not have an immediate interest in the production of products based on a certain technology, licensing to other institutions is considered to be a strategic emerging market for partnerships. In the light of current government policy in Brazil, which focuses on strengthening the technological capacity in biotechnology, these facts draw attention to the importance of improving the ability of S&T institutions to create and use patents, and to reinforce the instruments to expand their innovation.

Indicator 1 showed that, although the individual collaboration networks of B-M and the BI have increased considerably over the years, this was also accompanied by an increase in the average path length, modularity values and number of communities. Taken together, these results show that the networks became less connected over time. Even if the average degree has increased at B-M, the degree distribution is not evenly scattered across the network (data not shown). In the last period evaluated, the density values were also very low. Indeed, the increase in the size of the network can lead to a decrease in its density. This can happen because the amount of time individuals can invest in establishing and maintaining

Table 6. Data of patent networks at B-M and BI: Institutions

	Bio-Manguinhos			Butantan Institute		
	1999–2003	2004–2008	2009–2013	1999–2003	2004–2008	2009–2013
Number of nodes (institutions)	2	7	6	4	5	8
Number of links	1	8	7	4	5	12
Most frequent collaborators*	Fio-RJ (1)					USP (1)
		Fio-RJ (2)	Fio-RJ (2)			UNESP (1)
		USP (1)	UFRJ (1)	USP (2)	USP (1)	UFSC (1)
		Fio-BA (1)	Fio-BA (1)	IAL (1)	UNIFESP (1)	HAOC (1)
		UFPel (1)	Fio-PE (1)	InCor (1)	UNIP (1)	CMC (1)
		UFRJ (1)	UW (1)		CU (1)	UFSJ (1)
		USGov (1)				PathVcc (1)

*number of patents in co-inventorship
CMC = Children's Medical Center
CU = Cardiff University, UK
Fio-BA = Fiocruz-Bahia
Fio-PE = Fiocruz-Pernambuco
Fio-RJ = Fiocruz-Rio de Janeiro
HAOC = Oswaldo Cruz German Hospital
IAL = Adolfo Lutz Institute
InCor = Heart Institute
PathVacc = Path Vaccine Solutions
UFPel = Federal University of Pelotas
UFRJ = Federal University of Rio de Janeiro
UFSC = Federal University of Santa Catarina
UFSJDR = Federal University of São João Del Rey
UNESP = São Paulo State University
UNIFESP = Federal University of São Paulo
UNIP = Paulista University
USGov = US Government
USP = University of São Paulo
UW = University of Wisconsin, WI, USA

relationships is limited, and because of the nature of such relationships (Scott 2001). It is unlikely that researchers will work with many other researchers in the network because of the multiplicity of research topics. However, these parameters are very important when evaluated from the perspective of information flow. The denser the network, the more easily the information and knowledge will be transmitted and collectively built. In a less dense network, the information may be distorted when transmitted through a large number of different actors (Valente 2005). Similarly, a network with a large number of communities spreads the information quickly within a given community, but has problems disseminating it among different groups. Nevertheless, low densities also indicate considerable possibilities for developing and strengthening new relations. A higher density of organizational R&D networks leads to greater productivity (Reagans and Zuckerman 2001). It is also worth investigating if this structure is reflected in the intra-organizational network.

The identification of individuals with high degree and betweeness centrality, revealed by the two indicators, can serve many purposes for the organizations being analyzed. As product development processes often rely on academic research to evolve and develop new ideas and techniques (Toole 2012), these researchers can act as sources of information on technology trends and help to identify potential partners for cooperation. They can function as information leaders and their experience can reference strategic decisions on institutional investments in new technologies. Batallas and Yassine (2006) suggest that these individuals should form a 'mega-core of central nodes (high degree and betweeness centralities)' to improve the exchange of information, integration of systems, and innovation in their organization. In addition, individuals with high centrality can also serve as 'agents of change' for organizational interventions (Valente 2012). In the case of the organizations analyzed herein, it would be important to constitute a group that unites individuals from both networks (papers and patents) in order to gain a more holistic and integrated view of the projects and processes occurring within each organization.

The comparison of the most central individuals presented in Indicators 1 and 2 for B-M points to an overlap. This shows that the organization counts on the same individuals to deal with the challenges of technological innovation and scientific production, suggesting that industrial development at B-M is not isolated from the scientific community, as already seen in other research contexts in Brazil (Vasconcellos and Morel 2012). These individuals play a crucial role not only in the transfer of knowledge from one domain to another, but also have strategic importance in both settings. This fact is also aligned with the idea that science is increasingly related to technology and academic research greatly affects industrial research, especially in the biomedical industry (Toole 2012). At the BI, the individuals with high degree and betweeness centralities in the co-authorship network differ from those in the co-inventorship network. Nevertheless, this result does not exclude the possibility that these individuals interact in other ways that are less formal and less documented. Murray (2002) argues that the co-authorship and co-inventorship networks, although distinct, evolve together. Even when there is no overlap of personnel in the two networks, they interact to perform other activities, such as consulting, participation in committees, meetings etc. Certainly, scientists who are authors and inventors can have central roles in both networks. However, a central position in one network usually comes at the expense of such a position in the other network (Breschi and Catalini 2010).

There is also a marked difference in the sizes of the networks shown by the two indicators. Naturally, the co-authorship and co-inventorship data should be interpreted with caution, since the rules that govern them are different. While the authorship of a paper is the result of a process that may involve several members of a team and may vary according to the rules of the specific academic area, participation in an invention has a precise legal connotation (Breschi and Catalini 2010). At the same time, the number of authors of a scientific article is often greater than the number of inventors listed in a patent. However, even if the individual co-inventorship networks have a tendency to be smaller, the institutional networks do not necessarily need to reflect this feature.

The temporal evolution of the institutional networks shown by Indicator 2 reveals that both organizations show a tendency to cooperate with different institutions when filing a patent. This may occur because a diverse set of organizational partners could guarantee the exploration of new sources of knowledge. In fact, there are studies that suggest that in environments of great technological change, such as the health sector, it seems to be more important for organizations to establish relationships with several partners with whom they can jointly develop new technological knowledge (Hagedoorn and Duysters 2002; Shipilov et al. 2014). These shared experiences encourage organizations to add new dimensions to their collaboration, exposing the partners to new ideas and improving their innovative behavior and technological capabilities.

Indicator 1 shows a different pattern of collaboration in the institutional networks. In both organizations, there is a tendency to cooperate frequently with the same institutions, especially in the case of the BI. This organization may have adopted this behavior to achieve greater productivity or greater scientific performance in a short period of time (Yamakawa et al. 2011). This may also be related to the strengthening of the BI's own knowledge base, taking advantage of its previous experience with partners and of its accumulated confidence to increase the predictability and reliability of cooperation (Lavie et al. 2011). This could also be explained by the geographical proximity of these organizations: B-M is part of and located on the same campus as the Fiocruz-RJ unit, and the BI and the USP are on the same campus. Actually, it is natural for researchers to have a greater propensity to collaborate when working in the same region because the exchange of knowledge becomes easier (Abramovsky and Simpson 2011; D'Este et al. 2012). Geographical proximity brings organizations closer together, encouraging interaction with a high level of wealth of information and facilitating the exchange of both tacit and codified knowledge (Knoben and Oerlemans 2006). Also, sharing knowledge at a basic level facilitates a more effective communication between individuals and organizations (Boschma 2005). Clearly, the existing knowledge base of B-M and other units of Fiocruz is quite similar, since the organizations are part of the same parent institution and are focused on topics that are relevant to public health. The case of the BI and USP is analogous. Both institutions represent important roles in the national scientific development and the USP participates in much of the scientific production of the BI.

This partnership structure provides an important indication of the pattern of scientific collaboration of B-M and the BI. Several alliances with similar partners may yield fewer benefits than alliances with different partners, particularly because they provide access to less diverse information sets (Baum et al. 2000). It cannot be ignored that alliances with the same partners end up deepening the specific learning about that partner and, ultimately, adding experience which will help in managing future alliances with other partners (Hoang and Rothaermel 2005). However, some cognitive distance is needed to improve interactive learning, since knowledge creation requires complementary and often different knowledge (Nooteboom et al. 2007). Engaging in multiple alliances of the same type can hinder access to the complementary assets which are required for an organization to grow successfully.

Drawing from March's (1991) exploration/exploitation model,[1] Rothaermel and Deeds (2004) state that during the early stages of new product development processes, the organization conducts exploratory research involving the construction of new capacities in order to develop new knowledge or skills that it can later exploit to create value. Once the knowledge and potentially valuable skills are acquired during the exploratory process, the organization then turns to exploitation. This model is corroborated by a longitudinal study of 325 biotechnology organizations showing that institutions that use this strategy tend to have more products on the market (Rothaermel and Deeds 2004). In the light of these observations, the fact that both the BI and B-M have a more exploitive behavior (cooperating with the same institutions) with respect to research (which would be the initial phase of the product development process) and a more exploratory behavior (cooperating with different institutions) in the development of patents (which is the final stage), is somehow surprising. Considering that both B-M and the BI develop products for public health and have R&D sectors, and that the biomedical industry is heavily based on research and public science to develop innovations (Toole 2012), one would expect a more exploratory behavior with regard to the research conducted at these institutions, aimed at the acquisition of new knowledge and learning new technologies. Indeed, scientific research is fraught with uncertainty, has high costs and can take several years to generate results, but the returns can be high when it is successful (Atuahene-Gima 2005). At the same time, the final product development stage creates an immediate need to acquire certain additional skills, which could be obtained from existing/well-known partners. Exploitive behavior would be essential at this stage, in order to gain more speed.

The analysis of Indicator 2 also demonstrates that private companies do not participate in the co-inventorship networks at either B-M or the BI. In Brazil, the knowledge-producing sector is mainly represented by public organizations, while the user sector, which, through the innovation process, internalizes knowledge and generates goods and services, is almost always private. The recent resumption of industrial policy actions for health in Brazil intensified the establishment of a series of partnerships for productive development, involving both B-M and the BI. However, these partnerships primarily aim to internalize the technologies needed to produce strategic inputs, rather than to develop them. It is clear that this initiative is more directly focused on the need to overcome the gap in Brazilian industry, in order to make it more competitive. However, the benefits of strengthening the productive base and building national capacity cannot be fully achieved in the absence of an endogenous base for innovation. According to Gadelha and Costa (2012), the creation of this base requires a network of institutions to anchor the national strategy and strengthen the institutions of excellence with greater knowledge intensity. The scenario shown in this study shows that further initiatives are needed in order to establish a network which focuses on the development of products related to the well-being of society, introduces spaces for dialogue, formulates and implements public policies.

In this context, and based on the similarity of the two institutions, it would be expected that cooperation between them would be commonplace. However, over the period 1999–2013, only six published papers were co-authored and they did not develop any patents together. Essentially, there is a low level of coordination and complementarity in the actions of these two public laboratories and even some 'competing' projects, such as the development of a dengue vaccine. A strategic alliance between them could expand the R&D process in Brazil and make it more effective.

6. Conclusions

The method applied in this study allowed us to analyze the existing networks in which S&T organizations are engaged, as well as to identify their overlaps and differences. Thus, by evaluating the collaboration between public sector S&T organizations, this paper contributes in innovative ways by using co-authorship and co-inventorship network metrics to produce strategic information about these organizations. The indicators used show that the gains for managers and decision-makers mainly involve the understanding of important aspects of the collaboration pattern between organizations, which can act as a reference for establishing action plans and support strategic decisions. Thus, the use of network indicators is a very broad and useful diagnostic tool to evaluate the performance and support the development of S&T organizations.

It should be noted that there are drawbacks as well as benefits to identifying the networks of individuals in an organization. Such individuals may be reluctant to have their positions disclosed, fearing that the data demonstrate that they are more or less important than expected. Therefore, the data should be used with great caution and ethically. In addition, although partnerships provide a framework within which organizations can cooperate to innovate, they will only cooperate if they have sufficient incentives. Especially in the public sphere, government incentives, whether or not they are economic, are of the utmost importance to the promotion of inter-institutional collaboration. In addition to incentives, successful partnerships also require changes in organizational culture. It is the role of the organization to foster a culture of cooperation among its members and develop actions to mobilize and sustain these networks.

Note

1. According to March (1991), exploration is associated with the need for organizations to develop, experiment and learn from the attempt to collect and acquire new knowledge. Conversely, exploitation is linked to the use of existing knowledge for the sake of efficiency, internal experience, and gains in competitiveness (March 1991). While exploration is related to discovery, risk and innovation, exploitation refers to efficiency, refinement and productivity. Both networks are complementary and necessary to the creation and capture of value for an organization.

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