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Marco Antonio Vargas*
Fluminense Federal University
Niteroi, Rio de Janeiro, Brazil

Nathalia Guimarães Alves**
Rio de Janeiro Federal University
Rio de Janeiro, Rio de Janeiro, Brazil

Matias Mrejen***
Institute for Health Policy Studies
Rio de Janeiro, Rio de Janeiro, Brazil

Science, technology, and innovation in pandemic times: Covid-19 implications

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* Associate Professor at Fluminense Federal University, Department of Economic Sciences. PhD in Economics of Industry and Technology from the Rio de Janeiro Federal University; MSc and BSc in Economics from the Rio Grande do Sul Federal University. Coordinator of the Research Center for Industry, Energy, Territory and Innovation (NIETI/UFF). Email: mvargas@economia.uff.br
http://lattes.cnpq.br/6719286744850757 https://orcid.org/0000-0001-7954-8594

** PhD candidate in Industrial Economics of Technology at the Rio de Janeiro Federal University. MSc in Economics from Fluminense Federal University; BSc in Economics from the Rio de Janeiro Federal University. Email: nathaliaalves@globo.com
http://lattes.cnpq.br/9570562162314199 https://orcid.org/0000-0002-8178-3793

*** Post-doctoral Researcher Fellow at the Institute of Health Policy Studies. PhD and MSc in Economics from Fluminense Federal University; BSc in Political Science from the National University of Rosario. Email: mmrejen@gmail.com
http://lattes.cnpq.br/3748934931565397 https://orcid.org/0000-0003-2657-1445

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Abstract

The paper analyzes the impacts of the COVID-19 pandemic on the organization of and incentive to science, technology, and innovation in health activities worldwide and nationally, focusing on two aspects. One of them is related to the adopted mechanisms of coordination of and support to these activities in order to manage the pandemic. The other is related to the recent evolution of scientific production on Covid-19. This study highlights the strategic importance of public research and incentive institutions in organizing and coordinating science, technology, and innovation in health activities and the growing incorporation of new technological platforms associated with Industry 4.0. However, there are worldwide asymmetries in the production of scientific knowledge. So, a strategic State approach is crucial in order to coordinate public and private interests regarding health production and guarantee the population's access to health.

Keywords: Covid-19. Health Economic-Industrial Complex (HEIC). Science, Technology, and Innovation in Health. Bibliometric Analysis. Collaboration Networks.

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1. Introduction

Since the beginning of the Covid-19 pandemic, several countries have considerably expanded their support mechanisms to activities involving science, technology, and innovation (ST&I) in health. Such effort comes from acknowledging the crucial role of science and technology to manage crises of this magnitude and involves both funding for vaccine research and development projects (R&D) and other necessary products to immediately combat the pandemic, such as mobilizing scientific and technologic international cooperation networks.

Because of its scale and impacts, the pandemic managed to place science, technology, and innovation in health policies at a privileged space in the debate about sustainable development. This heightened the perception that had always been found in the 2008 crisis that robust National Innovation Systems and systemic, inclusive ST&I policies take center stage in handling crises. In addition, the effort to connecting ST&I health activities to manage the Covid-19 pandemic helped incorporate new technology platforms associated with Industry 4.0 with regard to R&D health activities. New technologies such as big data, artificial intelligence (AI), internet of things (IoT), cloud computing, etc., show how pervasive and multidimensional health innovations are. They have been utilized in several subsystems integrating the Health Economic-Industrial Complex (HEIC) (Gadelha, 2003).

On the other hand, the multidimensional crisis caused by Covid-19 exposed the fragile rhetoric of equality and collaboration between North and South globally, which used to be mentioned by multilateral bodies such as the World Health Organization (WHO). Although there are a few international efforts in health focused on specific intervention to treat epidemics, the quick dissemination of Covid-19 challenged the capabilities of governments and WHO to implement a coordinated global response to the pandemic (Tellez, 2020). One of the most remarkable examples of this fact is the significant increase in international trade protectionist practices that started to be adopted by several countries since the beginning of the pandemic. Inasmuch as the initial escalation of Covid-19 led to scarcity of various health products and inputs, such as personal protective equipment, hospital beds and ventilators, diagnosis test kits, etc., the national governments started to take actions ranging from restricting imports and health inputs to confiscating and misappropriating medical products cargo.[1]

The impact resulting from health products and inputs was notably higher in countries with a greater fragility in their productive base and a greater external dependency on acquisition of medications, vaccines, reagents, and medical equipment. Specifically in Brazil, of the 25 products listed as strategic health items to combat Covid-19 categorized the World Trade Organization (WTO) as equipment, one third of them are imported from the United States. This indicates a strong dependence. The United States, China, Germany, and Japan together account for over 70% of Brazilian imports of the 25 items on the list, e. g., ventilators, thermometers, X-ray devices, etc. (WTO, 2020).

In this aspect, the pandemic showed how important it is to strengthen the science, technology, and innovation infrastructure. This should be done by articulating this infrastructure with the various segments of the productivity health base as one of the key pillars to effectively build national sovereignty.

It is against this background that this article presents an exploratory analysis of the impacts of the Covid-19 pandemic on the organization and support of ST&I health activities in Brazil and worldwide. This article particularly investigates the pandemic implications regarding the global ST&I efforts based on two main aspects. The first one is related to ST&I activity coordination and support mechanisms that were adopted in developed countries and Brazil to stimulate quicker responses in terms of vaccines, therapies, and diagnosis tests to manage the pandemic. The second aspect is an analysis of the recent world/Brazilian scientific production on Covid-19 based on publications and patent data. This analysis enables one to assess the Brazil position in the world scientific production stage on this theme, as well as it helps explain the strategic importance of public research institutions

1 See: WTO. *Trade in medical Goods in the Context of Tacklink Covid-19. Information Note*. Publicated: April 3rd, 2020. Available: https://www.wto.org/english/news_e/news20_e/rese_03apr20_e.pdf. Access: Sept. 7th, 2020; and, DEUTSCHE WELLE. EUA são acusados de reter itens médicos destinados a outros países. Publication: April 4th, 2020. Availabe: https://www.cartacapital.com.br/saude/eua-sao-acusados-de-reter-itens-medicos-destinados-a-outros-paises/. Access: Sept. 7th, 2020.

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and promotion agencies in Brazil to generate, diffuse, and fund ST&I health activities. Likewise, the analysis on various areas integrating the production scientific knowledge on Covid-19 serves as a relevant indicator to understand how multidisciplinary and interdisciplinary health scientific/technological knowledge is. Also, it helps understand the growing incorporation of new technological Industry 4.0 platforms of health innovation knowledge databases.

This article is divided into three sections along with the introduction. The next section discusses the implications of the crisis caused by the pandemic for the ST&I activities and presents an overview of the support mechanisms implemented by some countries. The third section presents a bibliometric analysis of publications and patent data collected from the Web of Science and Derwent Innovations Index, which were related to Covid-19 in Brazil and worldwide. The fourth and last section of the technical note presents the article conclusions.

2. Implications of Covid-19 to articulate the global ST&I efforts

Since the 2008 international financial crisis, the potential economic and social crisis impacts on the science, technology, and innovation systems (ST&I) have become a topic of interest all over the world. Countries with more knowledge-intensive economies and more developed innovation systems suffered relatively less than countries that allocate fewer funds in ST&I and have more fragile innovation systems (UNCTAD, 2020).

Two peculiarities of the R&D activities explain the need of prioritizing them at crisis times. Since the results of investments in research and innovation activities are subject to high risk and uncertainty levels, one must maintain continuity guarantees and a long-term commitment to support ST&I. Moreover, the difficulties in developing and maintaining R&D activities for trained human resources demand research systems that guarantee appropriate incentives persistently and gradually in a context of a growing number of science and technology training processes (Abi Younes *et al*.,

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2020; UNCTAD, 2020). These peculiarities place the State as a central actor to equate public policies that enable one to articulate both the economic and social dimensions of innovations, especially in the health field.

After the Covid-19 pandemic emerged in the beginning of 2020, the research, development, and innovation (RD&I) processes were accelerated and financially supported by public and private institutions. Consequently, hundreds of vaccine clinical essays and candidate medicines, either new or already existing, have been registered since early 2020 (OECD, 2020; Liu *et al*., 2020). Testing multiple approaches increases the success probability of at least one or some candidates. However, experimenting without coordination and not adhering to shared research patterns compromise evidence production, higher the frequency of unconclusive clinical trials, as well as the use of time, financial, and human resources (Tellez, 2020).

One of the frontlines where international cooperation to manage the pandemic prove to be more relevant is the vaccine development and medication initiatives for immunization and treatment of Covid-19. With regard to new vaccines, the potential to protect entire societies from infectious disease outbreaks can only be achieved if the majority of the population is immunized. A large number of doses must be procured at affordable prices to meet the national health system demands (OECD, 2020). This demands international access to relevant technologies, low diffusion capacity, and access at low cost. All vaccines in development are new and will probably be patentable (OECD, 2020). Big pharmaceutical companies are involved in vaccine development projects to manufacture and distribute the product. Inasmuch as these companies are seeking profitability, patent protection and other mechanisms to protect intellectual property rights are central to their strategic engagement. However, these interests are in conflict with the greater interest of public health, which is to provide services in wide availability and at affordable prices to face a worldwide pandemic (Tellez, 2020).

Likewise, most clinical trial medications to treat Covid-19 is already authorized for other diseases, but medicines are already under protection of intellectual property in some jurisdictions. Several options have been emerging to manage intellectual property rights during this crisis, e. g., combining "open innovation" models, patent pools, and voluntary licenses (OECD, 2020; Tellez, 2020). The WTO article on Trade-Related Aspects of Intellectual Property Rights (Trips) enables some leeway for national governments to relax patent protection regulations. This may be done when they are part of national political aims to protect essential safety interests, including accessibility and public health protection. Nonetheless, the mechanisms of flexibility and safeguards foreseen by Trips are not, in themselves, a guarantee of medicines and other health inputs, especially underdeveloped countries (Casas, 2009). An example of these limitations is the medical equipment and inputs exports during the pandemic, such as the rules forbidding the purchase of materials and personal protective equipment imposed by the United States to the countries who received foreign aid funds (Baker, 2020). In addition, it was found that biopharmaceutical companies have not significantly helped with the patent pool established by the WHO. These companies have been receiving billions of dollars in funding. In most cases, they do not receive compensation for deadlines, prices, and countries that will have access to vaccines, or directly prioritize the largest financiers (Baker, 2020). The competition between the United States and China to obtain the vaccine is related to both the symbolic aspect of the geopolitical race between these countries and the aim of providing priority attention to their health demand nationally. Actually, China, the USA, and the European countries that form the Inclusive Vaccines Alliance (France, Germany, Italy, and the Netherlands) are actively working to guarantee priority access to the vaccine (Kupferschmidt, 2020).

The WHO has been trying to create international collaboration platforms that will accelerate RD&I processes and guarantee equal, global access to diagnoses, vaccines, and safe, effective treatments. One of these initiatives is the Access to Covid-19 Tools Accelerator (ACT-Accelerator), which is a global collaboration platform between public and private R&D institutions. Another initiative is the Covid-19 Technology Access Pool (C-TAP), a repository of patents, knowledge, and data on Covid-19 (UNCTAD, 2020). The patent pools work as a collection of patents of various owners, which are made available altogether for free or at a predefined value. The United Nations have adopted similar initiatives on previous occasions for drugs such as HIV, hepatitis C, and tuberculosis. Although participation is voluntary, in situations of public need the governments may also impose compulsory patent licensing (Abi Younes *et al*., 2020).

One of the most remarkable national initiatives to mobilize the ST&I system to manage the Covid-19 pandemic, is the Warp Speed Operation, in the USA. It received nearly US$ 10 billion dollars; of these, more than U$ 6.5 billion through Biomedical Research and Development Authority (Barda) and US$ 3 billion from the National Institutes of Health (NIH) (Cf.: HHS, 2020a). The Warp Speed Operation is a partnership between different bodies of Department of Health and Human Services (HHS), such as Barda and the NIH, and the Department of Defense. It has actions articulated with other USA federal government agencies and private companies. The operation aims to coordinate different HHS initiatives regarding the Covid-19 pandemic, such as Accelerating Covid-19 Therapeutic Interventions and Vaccines (Activ), a public-private partnership to coordinate research strategies and accelerate the development of possible vaccines and treatments, as well as NIH's Rapid Acceleration of Diagnostics (RADx) (Cf.: HHS, 2020a), an initiative focused on accelerating innovation in production and implementation testing and Covid-19 diagnosis technologies.

Some aspects of this operation have been criticized, though. In the context of a latent conflict between the USA and China, vaccines developed by Chinese companies were excluded from the possibility of receiving funding. In addition, the project explicitly includes provisions to prioritize the USA access to the first doses of the vaccine and is not linked to the USA participation in international initiatives to obtain vaccines (for instance, the WHO ACT Accelerator and the Coalition for Epidemic Preparedness Innovations - Cepi). Internally, this initiative has been criticized due to lack of transparency in the criteria for allocating funds in various companies[2] and the lack of mechanisms of articulation with the Activ initiative (Cohen, 2020a; 2020b).

2 The amount of funds is significant. The operation signed a contract with AstraZeneca that could reach US$ 1.2 billion and contracts that could reach $500 million with Johnson & Johnson and Moderna (COHEN, 2020b).

In Germany, the initiative of creating a network for coordinating research activities among the country's medical schools, to which the Ministry of Education and Research allocated €150 million. One of the main aims of this network is to unify data from all Covid-19 patients treated at university hospitals that serve to conduct research on disease clinical treatment and pandemic management, as well as policy-making decisions. In the United Kingdom, the government action strategy to manage the pandemic is linked to the Scientific Advisory Group for Emergencies (Sage). To respond to the Covid-19 pandemic, Sage has based its guidelines on conclusions reached by several specialized groups: the New and Emerging Respiratory Virus Threats Advisory Group (Nervtag), the Scientific Pandemic Influenza Group on Modelling (SPI-M), and the Independent Scientific Pandemic Influenza Group on Behaviours (SPI-B).

In Brazil, the federal government actions on creating mechanisms of articulation among the ST&I system actors to manage the pandemic has been controversial. The Ministry of Science, Technology, and Innovations (MCTI) created a committee at the beginning of the pandemic to advise and coordinate actions (the Network Virus MCTIC – RedeVírus MCTIC); the participation of the Brazilian Academy of Science (BAC), the Brazilian Society for the Progress of Science (SBPC), universities and research institutions also participate in this committee. However, the network guidelines did not have a central role to design federal government policies (De Negri; Koeller, 2020). The lack of actions to design policies to respond to the Covid-19 crisis in Brazil has been criticized by both national and international organizations linked to public health (Frente Pela Vida, 2020; *The Lancet*, 2020).

Despite these coordination issues, the Ministry of Health has been granting budget funds through various provisional decrees that were included in the Constitutional Amendment Proposition (CAP) 10/2020 named "War Budget". The federal government managed to allocate R$ 3 billion were allocated in funding actions to manage the pandemic that have been developed by Fundação Oswaldo Cruz (Fiocruz), one of the central links of the Brazilian Health Innovation System. These activities include expansion of the Covid-19 testing capacity, production of vaccines and medications, and health care programs that include a Hospital Center dedicated to Covid-19 seriously contaminated patients, as well as basic research funds.[3]

Following the Fiocruz example of strategic action within the national health innovation system, many initiatives created at universities, research institutes, and subnational governments have been instrumental in devising coordination actions for the ST&I system coordinators. For instance, the projects of the two most advanced vaccine testing phases in Brazil do not receive funds from the federal government. They are initiatives led by the Federal University of São Paulo (*Unifesp*, 2020) and the São Paulo state Butantan Institute (Fapesp, 2020). Moreover, various coordination and cooperation actions were developed between various ST&I system actors to share and produce knowledge on Covid-19. For instance, the CoVida Network – Science, Information, and Solidarity, created by the Center for Health Data and Knowledge Integration (Cidacs/Fiocruz Bahia) and the Federal University of Bahia (*UFBA*) (Fiocruz, 2020), or the Covid-19 Data Sharing/BR initiative, created by *Fapesp*, and the University of São Paulo (*USP*).[4]

The Brazilian government also allocated R$ 50 million to fund research on Covid-19 (R$ 30 million from the National Fund for Scientific and Technological Development – *FNDCT* and R$ 20 million from the Health Ministry). These public tenders, funded by the budget that had been previously made available by the Ministry of Science, Technology, and Innovations (*MCTI*), received credit of R$ 362 million for actions linked with R&D coming from *FNDCT* contingency funds. Besides, the state governments have destined additional funds to the research related to Covid-19 through specific tenders made by the Research Support Foundations.

3 Information Available on: http://www.portaltransparencia.gov.br/orgaos/36201-fundacao-oswaldo-cruz. Access: Sept. 7th, 2020.

4 *CoVida Network – Science, Information, and Solidarity*. (Site). Available: https://Covid19br.org/. Access: Aug. 30th, 2020; *Covid-19 Data Sharing/BR*. (Site). Available: https://repositoriodatasharingfapesp.uspdigital.usp.br. Access: Aug. 30th, 2020.

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3. The Covid-19 scientific production in Brazil and worldwide: institutional actors and ST&I collaboration networks

The analysis presented in this section aims to assess the Brazilian position in the international scientific production field on Covid-19. It also aims to identify the relative importance of several countries and institutional actors in generation, diffusion, and funding of ST&I health activities linked to the pandemic. In addition, the analysis on various areas integrating the production scientific knowledge on Covid-19 serves as a relevant indicator to understand how multidisciplinary and pervasive health scientific/technological knowledge is.

This analysis is based on publications and patent data collected from the *Web of Science and Derwent Innovations Index*. Both are made available by *Clarivate Analytics*.

The publication data of the main *Web of Science* collection focus on articles, editorials, book chapters, discussion texts, notes, journals, individual books and book series, reports, conferences, and other academic materials indexed in 23 languages in the period 1945-2020. The sample was observed for the first time in 1968. The database also provides information on the following items: knowledge areas; authors' names and coauthoring networks; authors' and co-authors' institution and affiliation; institutional and corporative authors; research consortiums; research funding organizations; names of magazines and publication meeting magazines.

The data made available on Derwent Innovations Index provide information about 30.5 million invention basic registers and patent families described in 65 million patent documents, with the coverage of 50 patent authorities worldwide. This information contemplates the period 1963-2020 and comprise indicators on knowledge areas related to patent documents, names, and inventors' codes and depositors, as well as class codes and International Patent Classification codes. Through data tabulation it is impossible to conduct analyses according to inventors' and depositors' countries.

The data was collected from the selection of a set of coronavirus-related keywords and the new version of the virus.[5] Even though the keyword set focused on the coronavirus, it comprised other virus variants, such as the SARS and MERS ones. This methodological option helped assess the coronavirus knowledge production evolution throughout a longer period.

The recent coronavirus mutation that made human contagion possible and originated the Covid-19 pandemic is a new event. However, the virus variants and its mutation possibilities had already been studied and monitored worldwide since the 1960s. Regarding the total number of publications, throughout the 1968-2020 period, 22,152 scientific publications were analyzed during the coronavirus. The world publications on the theme grew at a 22%-annual rate in the period 1968-2019 and suffered an abrupt 895%-growth if the January-June 2020 publications with the previous year are compared (Graph 1). The sustained growth of the number of studies in the period 1968-2019 indicates the cumulative character of scientific knowledge. Since new knowledge is developed from previously accumulated knowledge, the long-term investments in basic and applied research are critical to build basic and applied scientific-technological capabilities. They are related to the emergency capability of responding at specific crisis times.

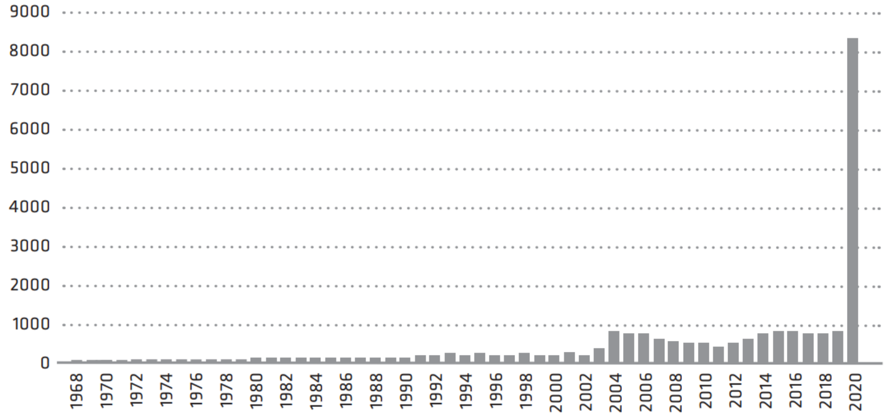
The participation of Brazilian publications on this these corresponds to 1.9% of the world publications in the period 1968-2020 and 2.1% when the January-June 2020 period was analyzed. The United States, China, England, Italy, Germany, and Canada stand out among the countries that published the highest number of studies on the coronavirus during the investigated period. Brazil published 420 studies on this theme. This number of documents is compatible with the number of publications from other developing countries like India (492), Russia (127), and South Africa (135).

5 The process of generating knowledge on the coronavirus is. The data was collected on June 11th, 2020, according to a keyword selection methodology related to the new coronavirus emergence: Coronavirus OR coronavirus OR 2019-ncov OR “ncov 2019” OR 2019ncov OR “Covid 19” OR Covid2019 OR Covid-2019 OR “Covid 2019” OR “cov 19” OR cov2019 OR “severe acute respiratory infection” OR “severe acute respiratory infections” OR “severe acute respiratory disease” OR “coronavirus 2” OR “coronavírus 2” OR sreg-cov-2 OR sars-cov-2 OR sars2 OR “sars cov 2” OR “novo coronavirus” OR “new coronavirus” OR “novel coronavirus” OR “nuevo coronavirus” OR “coronavirus disease”.

The knowledge area analysis on the coronavirus publications worldwide shows how far-reaching and multidimensional the process of generating knowledge on the pandemic is. Throughout the analyzed period, 217 knowledge areas were found to be related to research on the coronavirus. The great area of health sciences and biomedicine stands for 91% of world publications in the total analysis periods and 86% in 2020. Despite the expected prevalence of life sciences, knowledge areas related to technology such as Engineering and Computer Science (4% - 5%); Physical Sciences, e.g., Chemistry, Physics, and Mathematics (2%), Social Sciences, such as Psychology, Social Science, Law, and Economics (2 - 7%), and even Arts and Humanities, e.g., Philosophy of Science and Religion (0.3 - 1%) are found in the bibliography analysis.

The Brazilian publications are scattered into 63 knowledge areas in 2020 and 75 knowledge areas in the period 1989-2020. Table 1 presents the 20 knowledge areas with the highest publication registers in the world. In Brazil, besides the areas shown in Table 1, the Agriculture, Tropical Medicine, Parasitology, Psychiatry, other topics in Life Sciences, and Biomedicine, Ecology, and Environmental Sciences were found in the period 1989-2020. Knowledge areas such as Biophysics, Anesthesia, Ophthalmology, Biomedicine and Life Sciences, Applied Biotechnology and Microbiology, other topics in Social Sciences, Mathematical and Computational Biology, and Pathology are given a high relative importance by world publications on the coronavirus. However, they presented either low or zero frequency in Brazil.

Graph 1 - Worldwide publications on coronavirus (1968-2020)



Source: Own preparation based on data extracted from the *Web of Science* database (2021).

Table 1 - Areas of knowledge highly related to coronavirus research

Research Area	**Brazil (1945-2020)**	**Brazil (2020)**	**World (1945-2020)**	**World (2020)**
Virology	43	7	4558	258
Veterinary sciences	69	2	2229	107
General internal medicine	27	21	2153	1562
Infectious diseases	35	5	2090	434
Immunology	17	3	1790	222
Molecular biology and biochemistry	13	1	1701	241
Microbiology	27	2	1678	180

Research Area	Brazil (1945-2020)	Brazil (2020)	World (1945-2020)	World (2020)
Occupational, public and environmental health	36	28	1093	629
Other topics in science and technology	15	6	949	287
Pharmacy and pharmacology	4	3	893	311
Experimental research in medicine	10	2	868	243
Applied biotechnology and microbiology	9	0	861	67
Cellular biology	4	1	610	176
Surgery	4	4	484	459
Pediatry	13	5	405	192
Chemistry	2	1	405	135
Respiratory system	7	4	401	172
Neurology and neurosciences	5	5	394	226
Biophysics	0	0	357	48
Genetics and heredity	8	1	323	36

Source: Own preparation based on data extracted from the *Web of Science* database (2021).

The double counting of the world studies registered according to knowledge areas (2,658 in 2020 and 9,289 in 1968-2020) supports the multidisciplinary and interdisciplinary hypotheses of the coronavirus scientific production knowledge base. This scientific production is linked to several knowledge areas, and there are also linkages between those areas in the form of interdependency pairs. The knowledge base evolves from the creation of new, fundamental knowledge. It is also founded on preexisting and different forms of knowledge. Each publication can be linked to either one or more knowledge areas. This results in a network of knowledge areas that are direct or indirectly related via interdisciplinary flows of knowledge.

Figure 1 shows the knowledge area network of the coronavirus publications in the period 1989-2020 in Brazil. The 420 publications that were identified in the whole analysis period present 561 registers according to knowledge areas. It is possible to view the relative importance in terms of degrees of interconnectedness and centrality of knowledge areas: Public, Environmental, and Occupational Health; Research and Experimental Medicine; Infectious Diseases; Immunology, Biochemistry and Molecular Biology; Mathematics and Computational Biology; Ecology and Environmental Sciences; Virology, Veterinary Sciences; Mathematics; Microbiology; Medical Computing; Applied Microbiology and Biotechnology; Genetics and Heredity; Neurosciences and Neurology; Tropical Medicine; Parasitology and Cellular Medicine.

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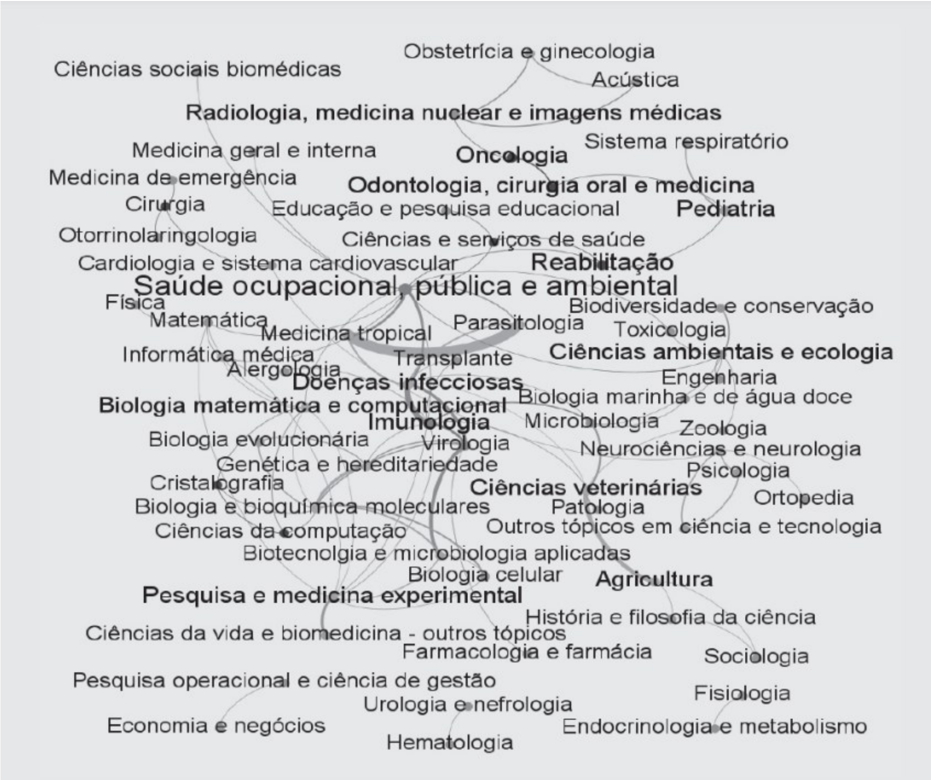
Figure 1 - Multidisciplinarity and interdisciplinarity of the areas of knowledge of Brazilian publications (1989-2020)



Source: Own preparation based on data extracted from the *Web of Science* database (2021).

The increasing addition of Revolution 4.0 technology platforms to health knowledge bases is seen in the articulations between areas such as Life Sciences and Biomedicine With fields such as: Mathematical And Computational Biology (110), Medical Laboratory Technology (93), Computer Science (81), Medical Computing (64), Information Science (14), Instruments and Instrumentation (13), Spectroscopy (11), Telecommunications (6), Microscopy (6), Automation Control Systems (3), Mechanics (3) Remote

Sensing (2), Image Science and Photography Technology (1).[6] In Brazil, incorporating scientific knowledge that support advances in Industry 4.0 in coronavirus studies is still timid, but this has intensified in the past two years after the addition of areas such as mathematical and computational biology (2), computer science (1) and medical computing (1), as well as areas such as mathematics (2), acoustics (2), and engineering (1). The close link between these areas and Life Sciences and Health Sciences are shown in Figure 1.

The pervasive technology in the coronavirus research is also found in the patent data analysis.[7] Between 1963 and 2020, 2,520 patents were identified and linked to coronavirus research. Of these, 178 studies were identified in 2019, and 143 studies were identified until June 2020. Observing the double counting of patents as per knowledge areas indicates that each patent refers to more than one technology knowledge area. In the total analysis time, 6,891 double counting exceeding documents were investigated. This means that there were cases in which the same patent identification code was double counted for being linked to more than one technology application area.

Table 2 shows the patent documents according to knowledge areas. Most coronavirus patents are linked to Chemistry, Pharmacy and Pharmacology, Applied Biotechnology and Microbiology.

6 In a smaller degree, Engineering (191), Mathematics (71), Acoustics (22), Operation Research and Management Science (9), Mathematical Methods in the Social Sciences (7), Metallurgy and Metallurgical Engineering (4), and Nuclear Science Technology (1).

7 The technology pervasiveness is the possibility of new combinations of technology knowledge that come from either technology paradigms or various technology fields. A possible example is the nanobiotechnological applications, in which each application described in a patent is linked to both biotechnology and nanotechnology, given the high pervasiveness of each technology paradigm.

Table 2 - Areas of knowledge highly related to coronavirus research

Areas of knowledge	Years		
	1963-2020	2019	2020
Chemistry	2.482	178	128
Pharmacy and pharmacology	2.428	175	122
Applied biotechnology and microbiology	1.922	143	105
Agriculture	1.052	100	55
Instruments and instrumentation	425	28	39
Engineering	365	29	30
Polymer Science	351	19	21
Food Technology	123	6	6
General internal medicine	90	1	14
Photographic Technology and Image Science	74	6	11
Computer Science	51	2	8
Materials Science	26		8
Water resources	5		
Electrochemistry	4		
Telecommunications	4		2
Nuclear science technology	2		
Automation Control Systems	1		
Building construction technology	1		1

Areas of knowledge	Years		
	1963-2020	2019	2020
Fuels and energy	1		
Metallurgical engineering and metallurgy	1		
Mineral processing and mining	1		
Optics	1		
Sports science	1		

Source: Own preparation based on data extracted from the *Derwent Innovations Index* database (2021).

The technology pervasiveness can also be found in the International Patent Classification (IPC). The 2,520 patents identified in the full period of analysis are associated to 2,995 IPC codes. It is common that the same patent refers to various codes of the same technology field. The codes are analyzed per patent subclass (4 digits). It was found that four codes represented 61% of the coronavirus patents per IPC in 2020 and 73% of the patents in 2019. The codes are as follows: preparations for medical, dental or toilet purposes (A61K); specific therapeutic activity of chemical compounds or medicinal preparations (A61P), Microorganisms or enzymes; compositions thereof; propagating, preserving, or maintaining microorganisms; mutation or genetic engineering; culture media (C12N); measuring or testing processes involving enzymes, nucleic acids or microorganisms; compositions or test papers therefor; processes of preparing such compositions; condition-responsive control in microbiological or enzymological processes (C12Q).

The Pharmacy and Biotechnology activities codes were prevalent. However, the patent codes linked to different technology fields such as advanced materials, advanced manufacture, computer technology, civil engineering, photonics engineering, nanotechnology, etc., supports the hypothesis of technology pervasiveness in coronavirus patents. Figure 3 shows the interdependent network in technological fields described as per patent subclasses (4 digits) for a restricted sample of the 500 most cited coronavirus patents in the period 1963-2020.

The interface between the technology advancement on coronavirus and the new 4th Technology Revolution is explained by ICP subcode patents such as: multiplex communication (H04J),[8] transmission of digital information (H04L), telephonic communication (H04M), pictorial communication (H04N); methods, circuits, or apparatus for establishing selectively a connection for the purpose of transferring information (H04Q); wireless communication networks (H04W); devices for producing, influencing, or using a flow of electrons or ions, e.g. for controlling (H01J); semiconductor devices (H01L); electric digital data processing (G06F); analogue computers (G06G); recognition of data; presentation of data; record carriers; handling record carriers (G06K); data processing systems (G06Q); image data processing or generation (G06T); microstructural devices or systems (B81B); machines, apparatus or devices for, or methods of, packaging articles or materials (B65B); apparatus for enzymology or microbiology (C12M); devices, apparatus or methods for life-saving (A62B); electrotherapy; magnetotherapy; radiation therapy; ultrasound therapy (A61N); devices for introducing media into, or onto, the body (A61M). The interrelation between this technology and the other technology paradigms that support the HEIC activities are shown in Figure 2.

8 Described as (IPC subclass code, number of verified patents).

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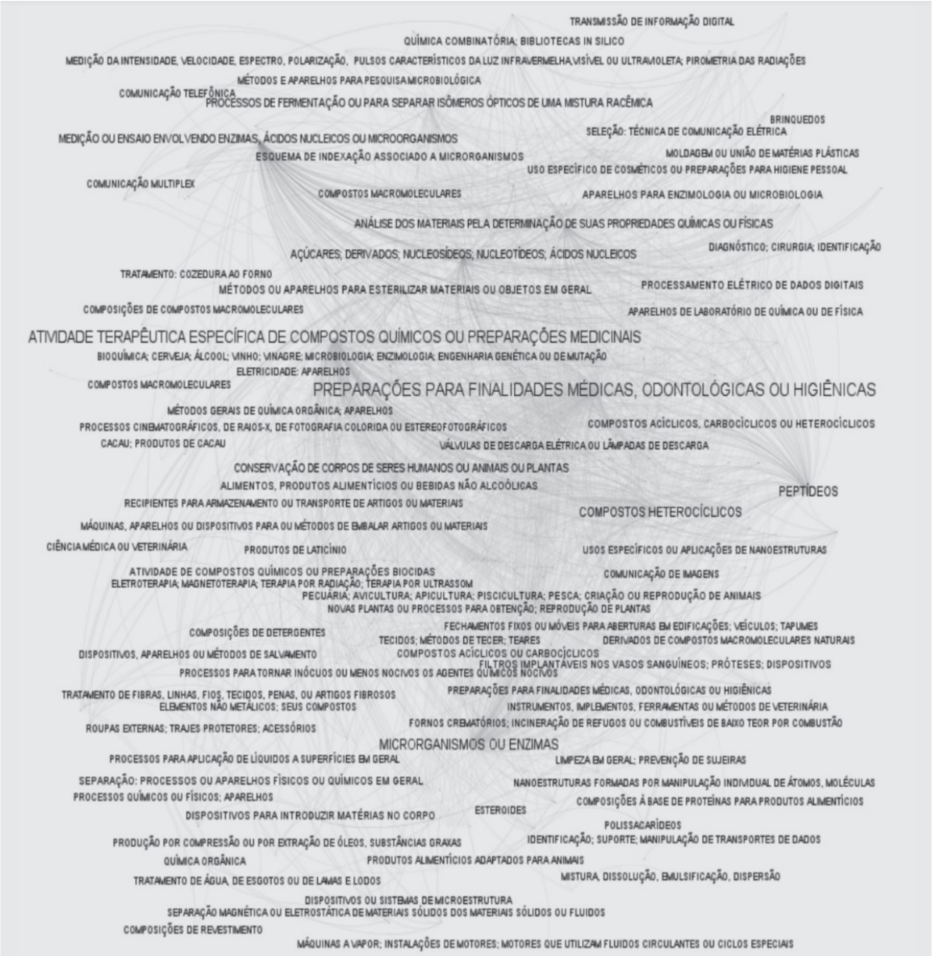
Figure 2 - Technology field network by patent subclasses



Source: Own preparation based on data extracted from the *Derwent Innovations Index* database (2021).

The following international organizations that most published studies on the new coronavirus in 2020 deserve highlight: University of London, Harvard University, University of California System, Huazhong University of Science Technology, Wuhan University, University College London, Harvard Medical School, University of Hong Kong, University of Toronto, Chinese Academy of Medical Sciences, Peking Union Medical College, University of Milan, and the Chinese Academy of Sciences.

In Brazil, USP stood out with 40 publications, and Fiocruz published 21 studies. Their coronavirus studies were internationally indexed in the period January-June 2020. Regarding author institutional affiliation of Brazilian publications on the coronavirus in the period 1989-2020, the following publications stand out because of their centrality and intermediation degree: the University of São Paulo; the Federal University of Rio Grande do Sul; the Oswaldo Cruz Foundation; the State University of Londrina; the State University of Campinas; the Federal University of Minas Gerais; the Federal University of São Paulo; the Federal University of Rio de Janeiro; and the Federal University of Paraná.

An important aspect of the Brazilian researchers' publications is the high frequency of scientific collaboration with international authors and institutions from countries such as the United States, England, Italy, Germany, Canada, France, Australia, Spain, China, and India.[9]

In terms of research funding structure, analyzing publications helps understand how important public funding is, both nationally and internationally. The United States NIH departments and institutes, the Chinese funding programs, such as the National Natural Science Foundation and the National Key R&D Program, as well as the European Union among the main financiers per number of funded coronavirus studies worldwide. The Brazilian National Council for Scientific and Technological Development

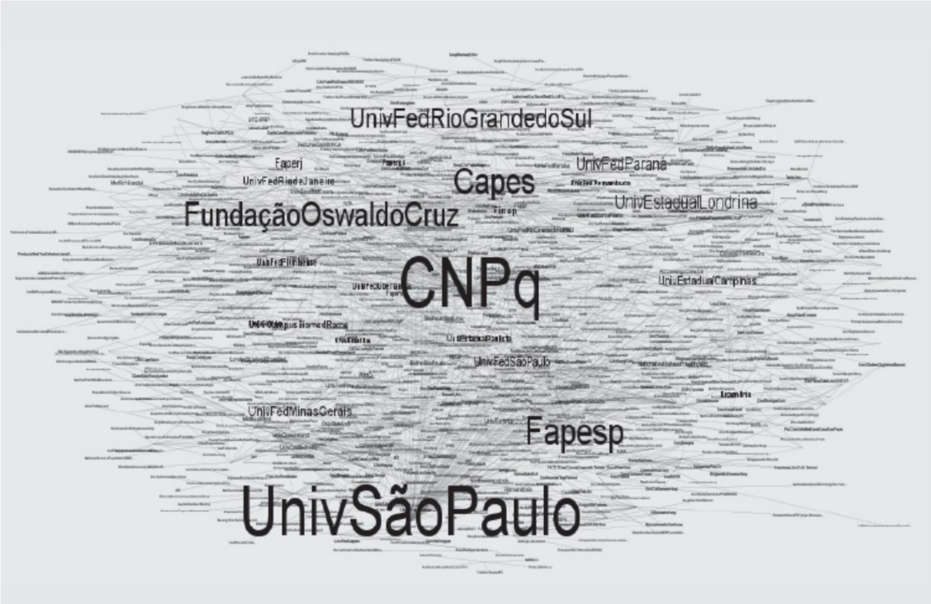
9 The main partnerships in international coronavirus collaborations were as follows: University of London, Brown University, Harvard University, State University System of Florida, University of Liverpool, University Campus Bio Medico Rome Italy, University of California System, University of Toronto, University of Virginia, Assistance Publique Hopitaux Paris, and Kings College London, as well as the Coronavirus Research Group. In 2020 there are collaborations via research alliances such as the Brazilian PrEP1519 Study Group, the CloroCovid-19 Team, the Parent in Science Movement, and the Viruses Executive Committee.

(CNPq) appears in the 19th position among the main international research support institutions. A comparison of all nomenclatures referring to CNPq in the Web of Science database helps identify at least 105 coronavirus studies supported by this Brazilian agency.[10]

Figure 4 shows the agency support network that funds study authors and co-authors involving at least a Brazilian researcher and their research institutions. The data clearly shows the importance of national agencies such as CNPq and the Coordination for the Improvement of Higher Education Personnel (Capes) to support Brazilian research on the coronavirus in the period 1989-2020. Other central institutions to support research were the Research Foundations in São Paulo, Rio de Janeiro, and Minas Gerais (Fapesp, Faperg, and Fapemig), as well as the Funding Authority for Studies and Projects (Finep) and Fiocruz to fund their research.

10 Each publication can involve a substantial number of authors and co-authors. Each author is affiliated to a research institution and can receive some form of support individually by national and international research support agencies. Therefore, a single study may be supported by multiple national and international funding agencies via co-authorship relations.

Figure 3 - Papers about coronavirus, Brazilian science and technology institutions and funding agencies for studies in Brazil (1989-2020)



Source: Own preparation based on data extracted from the *Web of Science* database (2021).

Finally, the analysis on patents helps identify the main coronavirus patent depositors in the analyzed period. Big pharmaceutical companies are predominant in human and animal health, followed by government agencies and universities.[11] Among them, giant pharmaceutical companies such as AstraZeneca, Novartis, Glaxo Smithkline, Schering, Janssen, and Johnson & Johnson deserve highlight. Wyeth and Pfizer companies, both controlled by the Pfizer Group, hold at least 80 coronavirus patents, placing Pfizer at a privileged position in the development of vaccines and antiretrovirals.

11 A great proportion of patents precedes the Covid-19 pandemic period. This result is coherent with the concession deadlines and patent confidentiality, the cumulative knowledge, and virus monitoring in a longer period of time. It was not possible to identify the Brazilian companies and institutions among the coronavirus patent holders.

Companies dedicated to the animal health segment such as Zoetis, Intervet, and Merial, as well as multisectoral 3M, also stand out because of their high number of patents. Integrated biopharmaceutical companies such as Coley Pharm, which is partially controlled by Sanofi-Aventis, Dutch-origin Crucell, controlled by Johnson & Johnson, and Kineta appear on the list of companies with the largest number of coronavirus patents (Table 3).

Table 3 - Largest companies holding patents on coronavirus (1963-2020)

Patent application	Years		
	1963-2020	2019	2020
Wyeth	43		
AstraZeneca	42		
Zoetis	39	1	
Pfizer	37		
Intervet Inc.	29	6	
Novartis	28		
Boehringer Ingelheim	27		1
3M Innovative Properties	25		
Glaxo Smith Kline	20		
Kineta Inc.	16		
Smithkline Beecham Corp.	16		
Schering	15		
Crucell Holland Bv.	12		
Coley Pharm Group Inc.	10		

Patent application	Years		
	1963-2020	2019	2020
Merial Ltd.	10		
Janssen	9	1	
Merial Inc.	9		
Johnson & Johnson	9		
Isis Pharm Inc.	9		

Source: Own preparation based on data extracted from the *Derwent Innovations Index* database (2021).

Virus mutation, human contagion, and the pandemic opens a window of opportunities that enables the emergence of new Biotechnology companies that aim to explore technology opportunities in this area. Biotechnology companies that did not historically have a high number of patents in coronavirus research, presented new patents in 2019 and 2020.

Chinese, Korean, and North American institutions are the predominant nationalities of the governmental agencies and non-profit research institutes that stand out as coronavirus patent holders. For instance, the US Department of Health and Human Services (HHS) holds 57 coronavirus patents, even surpassing the number of patents held by big companies and conglomerates individually. Besides the United States, governmental agencies and public institutes for the control and prevention of diseases in countries such as Korea and China work actively towards generating new science and technology knowledge that is commercially exploitable in coronavirus themes.

Non-governmental research institutes such as the Pasteur Institute and the Dana-Farber Cancer Institute, affiliated to the Harvard Medical School, are also shown on Table 4. Although they are not linked to the State, the research conducted by these institutes that are historically supported by public policy initiatives of several countries. The Pasteur Institute

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international network, located in France, includes 32 institutions located in 25 countries in all five continents. In Brazil, the Oswaldo Cruz Foundation is one of the 32 institutions that form the international network of the Pasteur Institute.

The leading universities in academic research on coronavirus themes hold nearly 13% of the patents on the theme. Alongside the universities listed on Table 5 that stand out for their total number of patents registered in the period 1963-2020, Huazhong Agricultural University (HZAU), in Wuhan, China, the Chonbuk National University, in South Koreal, the Da An Gene, a company that integrates the Sun Yat-Sen University structure, and the East China University of Science and Technology (both Chinese) stand out due to the number of patents in the period 2019-2020.

Table 4 - Government agencies and research institutes: largest coronavirus patent holders (1963-2020)

Patent application	Years		
	1963-2020	**2019**	**2020**
US Dept. Health Human Services	57		1
Korea Res. Inst. Bioscience and Biotechnology	25	3	
Tianjin Int. Biomedical United Inst.	17		
Inst. Pasteur	14		
Korea Cent. Disease Control Prevention	14	4	1
National Health Res. Inst.	12		
Inst. Beijing Viral Disease Control and Prevention	11	1	1
CNRS Cent. Nat. Rech. Sci.	11	1	
Dana Farber Cancer Inst. Inc.	11	1	

Patent application	Years		
	1963-2020	2019	2020
Cent. Nat. Rech. Sci.	10		

Source: Own preparation based on data extracted from the *Derwent Innovations Index* database (2021).

Table 5 - Universities: largest patent holders on coronavirus (1963-2020)

Patent application	Years		
	1963-2020	2019	2020
Univ. Tsinghua	20	2	
Univ. California	19	2	
Univ. Texas System	19		
Harvard College	17	4	
Univ. North Carolina	16	1	
Univ. South China Agric.	14	5	3
Univ. Kansas State Res. Found.	13	2	1
Univ. Nankai	12	3	
Univ. Emory	11	2	
Univ. Katholieke Leuven	11		
Univ. Henan Agric	10	3	1
Univ. Yonsei Ind. Academic Coop. Found.	10	2	1
Univ. Vanderbilt	10	1	1

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Patent application	Years		
	1963-2020	2019	2020
Univ. Colorado	10	1	
Univ. Fudan	10		1

Source: Own preparation based on data extracted from the *Derwent Innovations Index* database (2021).

4. Final Remarks

Science and technology have always been the most powerful weapons used by humanity to combat pandemics and sanitary emergencies. Like other global sanitary crises, the Covid-19 pandemic has imposed gigantic challenges to ST&I worldwide. Firstly, a pandemic of such proportions reaffirms the need of high articulation and international cooperation so that the efforts carried out in R&D activities are sustainable over time so that there is a productivity structure that can meet vaccine production needs and treatments and set rules that help manage intellectual property rights in a way that is compatible with the need of global and equitable access to potential vaccines and treatments.

Even though the WHO and international organizations have worked on several similar initiatives, the growing trade competition between the United States and China, along with the profound historical imbalances that characterize the access to vaccines and medicines in developing and underdeveloped countries, are serious threats to overcome the pandemic in all of its dimensions.

The regional blocs and national governments of the developed countries reacted to the challenges imposed by the pandemic. They created additional funding mechanisms for academic research in Covid-19 themes and R&D activities directly to produce an effective vaccine in the shortest possible deadline. Besides, the national governments managed to create several coordination and articulation mechanisms among different ST&I system activities to boost Covid-19 research and development activities. In Brazil, despite the insufficient institutional articulation to take measures to manage the sanitary and socioeconomic dimensions of the pandemic, the universities and public research institutes played a key role alongside state governments to articulate and coordinate ST&I activities to manage the Covid-19 pandemic.

As it occurs all over the world, the production of scientific knowledge on the coronavirus in Brazil is dominated by universities and public research institutes. Institutions such as Fiocruz and USP stand out for their national and international relevance in scientific production on the coronavirus. Nationally, the production of scientific knowledge on the coronavirus has large contributions from public federal universities.

Furthermore, these institutions play a crucial role to establish international scientific collaboration networks. They are found in the volume of co-authorships in publications such as the participation in collective RD&I projects. The partnership established between Fiocruz, Oxford University, and AstraZeneca to buy batches of vaccines and transfer technology to manufacture a Covid-19 vaccine using the Technology Order tool (Etec). This constitutes one of the examples on the importance of the role played by public research institutions to coordinate ST&I activities to manage the pandemic in Brazil.[12]

The importance of public support to ST&I activities in the context of Covid-19 is also reflected in the high participation of public research funding institutions. The considerable number of active universities, public research institutes and research funding agencies were in tune with the literature on economy of science, technology, and innovation. However, they only gain notoriety at crisis times because of the pandemic sanitary and socioeconomic impacts.

On a global scale, institutions such as the NIH in the United States, the National Natural Science Foundation in China, as well as several public

12 The Ministry of Health signed a 127-million-dollar agreement for purchasing vaccine batches and transferring technology so that production can be completely internal and national (FIOCRUZ, 2020).

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national institutions to foster science in Japan, Canada, and European Union countries. In Brazil, institutions such as CNPq, Capes, and Finep, as well as research support institutions on state level played a key role to foster scientific research nationally. This heightens the preoccupation on the sustainability of scientific activities in the face of constant cuts and contingencies in the public ST&I budget that have been observed in the country in the past few years.

Finally, the analysis presented in this article reinforces the perception on the existing imbalances in the generation, diffusion, and funding of research on health worldwide and stresses the need of strategic action by the State to manage this process. Providing vaccines and medicines at affordable prices to health systems in many countries, especially the poorer and developing ones, shows how important the State is as a central instance to articulate public and private interests and focus on the social interest. This issue has linkages with the unequal distribution of scientific and technological capabilities among countries, as well as questions related to intellectual property, commerce, provisioning inputs and end products, resource availability, institutional and regulation framework, as well as the characteristics and idiosyncrasies of the national health and innovation systems in each country.

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