RESEARCH ARTICLE

The transformation of medical research in Mexico: A structural analysis of thematic domains, institutional affiliations, authors' cohorts, and possible correlations

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ABSTRACT

Global research on medical and health-related issues has experienced a profound reconfiguration over the last 30 years. The rise of new areas of inquiry has transformed the medical research landscape as staff with medical training gradually relinquished their prominence and specialists from other disciplines raised their profile within research teams. Given this, research priorities seem to be shifting increasingly towards laboratory-based and innovation-oriented research lines. The unfolding of these shifts in nonhegemonic countries such as Mexico is still to be understood. This paper surveys structural changes in Mexican medical research from 1993 to 2021 by observing temporal aggregation of authorships, emerging thematic features, and institutional affiliation patterns. It also explores correlations between these findings and their possible explanations. The results allow us to empirically describe significant changes in medical research done in Mexico. We detected periods of stability in authorship allowing us to describe stages in the accumulation of research and development (R&D) capabilities. The identified semantic patterns allowed us to characterize this transformation, observing subsequent stages of an accumulation and specialization process that began in the mid-1990s. Moreover, we found divergent thematic and institutional patterns that point towards a growing gap between research conducted in health institutions and scientific ones.

1. INTRODUCTION

Medical research is a multifaceted scientific field involved in a rapid transformation manifested in the specialization and differentiation of its various branches. Historically, medicine has stood out among academic science for being tightly connected to both industry and the State (Edgerton, 2008, p. 198). Over recent decades, scientific publications have become increasingly oriented toward medical applications (Wong, 2019). These changes can be understood from at least two different perspectives. On the one hand, new discoveries and findings allow increasing transformations based on developments that carry scientific and technological relevance. These advances have implied changes in the profiles and background of researchers (Keating & Cambrosio, 2003). How new discoveries and developments are received and further developed becomes a crucial issue in understanding the different

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ways in which knowledge is created. Science does not happen in closed and isolated spaces; on the contrary, it is a form of communication between people (Secord, 2004). The circulation of knowledge is perhaps a crucial feature of modern science, as it remains a collective effort that requires the participation of multiple parties, even if they take very different roles (Kreimer, 2006). Still, distinctive research profiles emerge in specific circumstances, with foci of interest, institutional structures, and scientific cohorts that emerge tied to geographical and temporal coordinates.

On the other hand, countries of the Global South, even though standing in a disadvantaged position in the international division of scientific labor, still have margins for influencing the production of knowledge (Losego & Arvanitis, 2008). National policy then becomes a privileged tool to address these challenges. In Mexico, the low participation of the private sector in research financing has made government sources responsible for almost 77% of the allocated funds, one of the highest in Latin America (RICYT, 2022). Still, resources dedicated to R&D are only 0.31% of the gross domestic product (GDP) (Quiroga-Garza, Garza-Cisneros et al., 2022).

In nonhegemonic countries, such as Mexico, this becomes particularly relevant due not only to the importance that public policy has had in the attempts to direct and promote research addressing the so-called National Problems (Dutrénit, Santiago-Rodríguez, & Vera-Cruz, 2006) but also to the limitations of public funding to address them (Natera, Rojas-Rajs et al., 2019a). In recent years, in Mexico and many Latin American countries, the development of research capabilities has been at the core of science policy efforts. Perhaps the more notable ones in Mexico are the development and training of new researchers and the increase in scientific production (CONACYT, 2002, 2008, 2014, 2018). Medical research stands out as one of the most relevant areas for these efforts (González-Brambila & Veloso, 2007; Lancho-Barrantes & Cantú-Ortiz, 2019), while closely related to a complex and compartmentalized health system (Frenk, González-Pier et al., 2006; Gómez-Dantés, Sesma et al., 2011) marked by inequality, high administrative costs and a structural financial imbalance among its users (OECD, 2016). This makes medical research stand out as a relevant object of inquiry as is a place where different professional profiles (i.e., physicians and professional researchers) converge in research activities. Given this scenario, publications by active Mexican researchers become a key element in characterizing and depicting the broad scope of actual transformations in the national research landscape related to the matter.

Medical research in Mexico lies entangled between transformations of global reach and a set of policy efforts on a national scale rolled out in a complex scenario with research communities of different backgrounds. As these changes slowly aggregate through time, they cannot be grasped without considering a significant time period. Mexico having devoted its policy efforts in the last decades to training new scientists and growing its publication output, while prioritizing health-related research, it remains relevant to understand how this endeavor has unfolded. Therefore, this paper aims to answer the following questions: how did the production of medical knowledge evolve in Mexico from 1993 to 2021? What are the key cohorts of authors supporting these transformations? And how does this relate to the thematic domains and institutional collaboration structures that support this evolution?

To do so, we study the publication patterns and underlying structures of the production of knowledge of Mexican researchers in medicine. Hence, this paper concentrates on a historical analysis of Mexican authorships and publications. To understand the evolution in the

accumulation processes of research capabilities, we observe a set of top authors and their temporal distribution. After doing so, we detect periods of authorship stability. We continue to identify main research interests by observing specific semantic features in the published documents. We looks for relevant semantic and institutional patterns that help to portray this transformation. Then, we focus on establishing relations between the structural features detected while discussing the implications of these findings. Finally, by contrasting the results, we reflect on the method used and the critical transformations in the structural features in Mexico's medical research.

2. LITERATURE REVIEW

Medical research has steadily increased its relevance and its size in recent decades (Wong, 2019). Changes such as sedentary lifestyles, stress, the rise of diets with an increased intake of fats and sugars, the rise of new pathogens, or the general aging of the populations are examples of the social transformations that have raised the importance of knowledge on medical issues. Such transitions have transformed the prevalence of some pathologies and marked the emergence of others. Even if the importance of academic science conducted in connection to medicine has been there since at least the 19th century, these social transformations seem to be putting health-related research on the rise. In medicine, a close relation between professional practice and academic science has made it stand out, establishing tight connections to industry and the state (Edgerton, 2008, p. 186). Although knowledge construction implies an interactive process between diverse parties (Secord, 2004), it entails different roles and positions with cognitive implications resulting from subordinate relations (Kreimer, 2006). Medical knowledge circulates marked by this close relation between practice and research. Then, it becomes a privileged space to map scientific transformation in specific coordinates.

In the case of Mexico, the health sector stands out as an important area for scientific capacity building (Torres, Jasso, & Martínez, 2014). At the same time, the impact of specific disorders—such as diabetes mellitus—has proven to have significant economic impacts (Barraza-Lloréns, Guajardo-Barrón et al., 2015). Diabetes and related metabolic diseases represent about 20% of the preventable deaths in Mexico (Quiroga-Garza et al., 2022), becoming a national priority from 2000 onwards (Dutrénit, Natera et al., 2021, pp. 3–18). Likewise, unforeseen health emergencies, such as that linked to the COVID-19 pandemic, have shown the importance of scientific capabilities to address emerging health and social challenges (Diéguez-Campa, Pérez-Neri et al., 2021; Raut, Sah et al., 2021). Health research in Mexico appears both as an increasingly relevant field of study and one that inserts itself into the local scenario with specific threads.

In this North American country, medical research appears tightly connected to structural features of the Mexican health system, a system marked by the lack of integration between its different branches (Gómez-Dantés et al., 2011). In Mexico, not only are public and private health providers highly decoupled, but the public health services are financed, managed, and carried out by different institutions. Thus, patients with health insurance receive attention from diverse public providers according to the nature of their employer; ISSSTE provides care for public servants and IMSS for the remaining insurees. Patients without any insurance are treated mainly by the Secretariat of Health (SSA) and its hospital network.

On top of this, the most important Mexican higher education institutions (HEIs) do not rely, as in other countries, on academic medical centers or university hospitals to conduct medical

research and training. The training of physicians in different specialties is accomplished mainly in national specialty institutes, relatively autonomous but under the coordination of the Secretariat of Health. Thus, the institutional complexity of health services in Mexico affects research activities, as access to critical resources remains scattered across different institutions.

Knowledge produced under these conditions remains a relevant object of study, as it helps when grasping scientific change and describing features of its changes in noncentral locations. Scientific change has been understood as a differentiation process that results from the disaggregation of research objects deriving from simultaneous processes of change and stability (Abbott, 2001, pp. 3–33). This distinction and branching process comes with the increasing size of a community of inquiry, something tightly intertwined with the disaggregation of the objects of knowledge. In each generation, specificity increases as each lineage splits into subordinate parts. This paper aims to chart the development and evolution of such a research landscape as a way of empirically addressing and discussing the process of scientific change in Mexican medical research.

As stated, medical research entails the complexity of a close connection between research and practice, while remaining a relevant arena for its industrial and political ramifications. Still, an ongoing differentiation process has been reported by members of this community of practice: medical doctors. Internal observations that physicians have made on the changes in their profession and the relation with knowledge production activities offer a glimpse of the ongoing generational changes in this research landscape. For example, in the United States, a significant decrease has been reported in the proportion of physician-researchers who apply for research funding (Nathan, 1998) and those who receive it (Martin, Lindquist, & Kotchen, 2008). When documenting this shift, claims highlight the critical role that research-focused physicians play in applying new medical knowledge (DeMaria, 2003; Wyngaarden, 1979).

In recent decades the medical research ecosystem seems to have increased its complexity and undergone various changes that pushed forward the disciplinary distinction. High costs, deferred results, more competitive funding, new regulations, and lack of trained research personnel, among others, have been some of the challenges for clinical research (Sung, 2003). Training physicians to conduct research activities has been proposed to respond to the increase in investigations conducted by researchers not trained in medical schools (Goldhamer, Cohen et al., 2009). Nevertheless, changes in medical research structure seem to be structural and long-lasting. Scientific staff specialization and professionalization appear to be entangled with the rising complexity and diminishing participation of physicians in medical research.

The decrease in the importance of medical staff in research can be thought of as an evolution of the order of things established in the early postwar period (Rigal, 2008; Valier & Timmermann, 2008). There, standardized experimental medicine started playing a critical role in mobilizing statistics and quantitative tools to evaluate medical care, assess the success of the therapeutic intervention, and orient the planning of health services and laboratory research.

Keating and Cambrosio (2003, p. 43) described an analogous process, one that reshaped the content of medical sciences as the rise of new entities, both existing as biological entities and pathological signs. In this new emergent model, a new "relation between biology and the clinic" is at the center. This is a shift that allowed medical biologists to increase their intervention in "the clinical realm and reshape the organization and content of medicine." In research,

this translates into a new set of skills and interactions that support the development of new research agendas.

In this transforming research landscape, one defined by rising standardization, new scientific platforms, and specific kinds of collaborations attached to it, the importance of publishing authors remains crucial. In a national context, where the training of new scientists remains a priority, changes in publishing authors offer a way of assessing the rhythm of these shifts. Individuals' experience over time constitutes a salient social force because it connects the past with the present and the future (Abbott, 2016, pp. 3–15). Hence, the historical recurrence of authorship can be considered a key indicator to assess the evolution of the different stages of a national research landscape. Moreover, in biomedical sciences, authorship results from coproduction between junior and senior researchers (Biagioli & Galison, 2003, pp. 309–311). Hence, cohorts of authors offer a good data source to map the transformation of a specific intermediate social group—medical researchers—and it is to be expected that the repetition or nonrepetition of prominent authors will allow us to capture the changes in the historical structure of prominent roles in laboratories and research teams over the years. Moreover, there is a trend towards cooperative scientific research due to the rapid diffusion of research outputs, stimulated through the Internet, and the complexity of interdisciplinary research topics (He & Zhou, 2022).

It becomes relevant to take a look at the overall research landscape of medicine in Mexico, as research in health sciences has grown the most, between 1980 and 2001, compared to other areas of knowledge (Gonzalez-Brambila & Veloso, 2007, p. 1041). Also, between 2007 and 2016, medicine stood out as one of the most productive disciplines in Mexico (Lancho-Barrantes & Cantú-Ortiz, 2019, p. 506). Even though the number of publications has increased constantly, from the 22 research areas analyzed in which the Essential Science Indicators (ESI) scientific publications are classified, Clinical Medicine had one of the lowest participations, around 0.5% (Toche, 2019).

Regarding Mexico, it is essential to keep in mind that the training of new researchers and the increase in scientific productivity have been central points of Mexican STI policy during the last decades (CONACYT, 2002, 2008, 2014, 2018)—a policy sustained on the expectation that the resulting outcomes would greatly contribute to solving the so-called National Problems (Dutrénit et al., 2006). Nevertheless, research studying diabetes-related projects with public funding in Mexico from 2002 to 2014 found them not to have a significant "consideration of knowledge use." (Natera et al., 2019a). Mexican STI policies seem to place incentives that are overly oriented towards basic research, barely promoting the actual use of the new scientific knowledge. This appears as a repeated threat for developing countries, as a general mismatch between the research agendas and the needs of health systems has been reported (Natera, Tomassini, & Vera-Cruz, 2019b).

Like other developing countries, Mexico can be thought of as a nonhegemonic country, which cannot fix new research agendas but still steers its way in the international scientific landscape through STI policy and by choosing specific topics and partners (Losego & Arvanitis, 2008). This means that a national research landscape emerges from a blend between policy and the agency of its members. As medicine lies among the most relevant areas of research, in terms of policy and productivity, the question of the evolution of this research domain connects not only to policy-induced transformations but also to the specific shape it takes in terms of the groups of active researchers, the topics on which they publish, and the collaboration structures that support it. Shedding light on the structural features of these transformations becomes a key element in grasping the shaping trends of this research

space, and while at it, providing empirical material to describe the reach of specific forces in this transformation.

3. MATERIALS AND METHODS

We retrieved the information from the Web of Science (WoS) database. The reasons behind using WoS over other databases are that The focal points of PubMed are life sciences and biomedical disciplines whereas Scopus and WoS cover all scientific areas, including multidisciplinary fields (AlRyalat, Malkawi, & Momani, 2019); it has been shown that in WoS the distribution of non-English documents is more homogeneous, with the widest representation of life sciences and medicine (Pranckutė, 2021; Vera-Baceta, Thelwall, & Kousha, 2019); and other studies related to the Mexican system have been carried out using WoS (González-Brambila et al., 2013; González-Brambila & Veloso, 2007).

We wrote a targeted query to capture publications related to medical specialties and subspecialties. To establish the areas to focus on, we resorted to a simplified categorization based on the Association of American Colleges standards (St. George's University, 2021). We did so because it represented most of the medical fields that serve each of the realms of care. Although we assume that these specialties localize in the Mexican case as part of negotiations and pre-existing institutional, infrastructural, and material relations, we also take them as a valid criterion that mirrors the standardization processes that support the universal character of medical procedures (Timmermans & Berg, 1997). Based on a comprehensive analysis of these specialties, and after multiple iterations, data retrieval was pursued using a query line that focused on areas of interest to the practice of medicine:

> CU=Mexico AND (SU=ANATOMY OR SU=MEDICAL ETHICS OR SU=BIOLOGY OR SU=GENETICS OR SU=MICROBIOLOGY OR SU=BIOPHYSICS OR SU=NEUROLOGY OR SU=DENTISTRY OR SU=ONCOLOGY OR SU=DERMATOVENEROLOGY OR SU=OPHTHALMOLOGY OR SU=EPIDEMIOLOGY OR SU=OTOLARYNGOLOGY OR SU=FORENSIC MEDICINE OR SU=PATHOLOGY OR SU=GYNECOLOGY OR SU=OBSTETRICS OR SU=PEDIATRICS OR SU=HISTOLOGY OR SU=EMBRYOLOGY OR SU=PHARMACOLOGY OR SU=HYGIENE OR SU=PHYSIOLOGY OR SU=PATOPHYSIOLOGY OR SU=BIOCHEMISTRY OR SU=PSYCHOLOGY OR SU=PSYCHIATRICS OR SU=IMMUNOLOGY OR SU=RADIOLOGY OR SU=INFECTIOUS DISEASES OR SU=SOCIAL MEDICINE OR SU=TELEMEDICINE OR SU=SPORTS MEDICINE OR SU=INTERNAL MEDICINE OR SU=SURGERY)

The resultant registers were cleaned to ensure the quality of the data. The database was retrieved with coverage up to June 2021, producing 55,783 records (Milia, González-Brambila, & Ponce Sánchez, 2022). The results were processed using the CorText platform (Breucker, Cointet et al., 2016). Based on the authorship equivalences, we computed the optimal division in temporal periods using the statistical criterion of Tibshirani, Walther, and Hastie (2001). This process detects frequency distributions to produce a matrix based on the cosine distances between the distributions of authors for each pair of years. This represents the distance between the composition of a data set in 2 different years, and is then able to detect emergent periods of time based on the most productive researchers.

The analysis included authors based on a minimum publication threshold to capture the most relevant researchers. Then, it considered only those with at least 35 articles published between 1993 and 2021, a total of 871 researchers. These authors were cosigners in 34,349

documents—62% of the studied registers. For the analysis, authors were not distinguished by nationality to represent the population effectively active during the years studied.

To assess the landscape of medical research in Mexico, we resorted to semiautomated textual analysis, a technique used to identify thematic domains in scientific publications (Barbier, Bompart et al., 2012). Using the CorText platform, we detected the 250 most representative terms, resorting to natural language processing techniques for the semantic analysis. Multiterms were detected with a maximal length of three words. The detection process focused on extracting noun phrases from the fields: titles (TI), abstracts (AB), author keywords (DE), and keywords calculated by the WoS (ID) algorithm.

We processed our corpus in a two-tier approach: first using classical linguistic processes to define a set of candidate noun phrases; and second, establishing the most relevant multiterms and selecting them. To define a list of candidate terms, textual fields were processed using part-of-speech tagging, chunking, and normalizing techniques. Later, the resulting multiterms were gathered into stemmed classes.

To select the resulting multiterm groups, relevant terms were processed to discard those with no special meaning, selecting them by high unithood (Frantzi, Ananiadou, & Mima, 2000). Then, terms with high termhood (Kageura & Umino, 1996) were chosen. This was to avoid including descriptors that, although they may be very frequent in the corpus, are not useful in characterizing the content of the documents. Multiterms with low termhood were identified using a similar approach to van Eck and Waltman's (2011) and selected using a second-order analysis as described by Bernard, Andrei et al. (2015, p. 57). As a result, only the most specific multiterms were kept. Finally, the resulting terms were manually curated, eliminating empty and redundant descriptors and harmonizing synonyms. We performed a co-occurrence analysis on the resulting terms.

Using a hierarchical community identification algorithm, namely the Louvain algorithm (Blondel, Guillaume et al., 2008), clusters of terms were detected. Modularity, a parameter that measures the density of connections in a community (Lambiotte, Delvenne, & Barahona, 2014), was set to 1.5 to detect groupings with a greater number of nodes given the level of detail (250 terms) used. For this optimization, we used an algorithm to define a parameter resolution value (Aynaud, 2020). Given the nondeterministic nature of this process, slight variations can happen in different computations. Nevertheless, given the size of the calculated networks, additional runs were computed and still reported a community structure consistent with those included here. Each cluster was interpreted and contrasted with the analytical categories presented using distant reading techniques to situate relevant terms in context. Some of the emerging labels were manually curated to better express their analytical relevance. These criteria were incorporated into the interpretation of the results.

Signatures in medicine for Mexico are a problem due to the great variety and the lack of standardization in international databases. As we have stated in this research, this is a space in which at least two types of professionals converge. On the one hand, there are personnel with medical training and employed in the different health institutions; on the other hand, there is a variety of scientists not trained in medicine but whose research is relevant to medical discussions. Although the standardization of signatures on scientific articles has advanced significantly, it has done so, above all, in institutions that are an active part of the scientific system. In contrast, the institutional affiliations of health professionals are characterized by being highly variable, unsystematic and, in some cases, even chaotic. The designations include multiple institutional names, different ways of simplifying the names, and even typing errors.

As the methodology of this research requires information on the participation in research activity of the institutions of the Mexican health system, we have proceeded to enrich our database with institutional information. For this purpose, we have constructed a dictionary[1] including descriptors for the main institutions of the Mexican scientific-technological system and the Mexican health system. These descriptors allow us to identify the institutions within the addresses (C1) reported by the authors.

This has left us with 2,367 variations to describe a total of 454 institutions, both Mexican and foreign. From this dictionary, we have generated a new variable (AD_1) detecting the mentions of these institutions as descriptors of the articles in the database. This method has allowed us to solve our database's structural problem and provide more precise information to answer our research question. Of the total number of documents (55,783) that make up the analyzed sample, the signatures of only 5.3% (2,960 documents) could not be normalized with this technique, extracting at least one institution from the signature.

We used community-detection algorithms to find relationships between institutions with at least 45 documents (301) published in the studied period. This threshold allowed us to drop institutions with very few documents, allowing us to build a better-structured and more stable collaboration map. Following this, institutional collaboration patterns were detected. Based on these results, we looked for relationships between the detected thematic domains and the emergent groups in institutional collaborations by plotting a nonhomogeneous network. Then, the evolution of semantic and institutional mappings was traced to understand the composition of these fields and its relationships over time.

4. RESULTS

4.1. Temporal Authorship Structure

To better understand how the cohorts of researchers were active in medical research in Mexico between 1993 and 2021, we have resorted to detecting periods of stability in the authorships of the papers included in our database. As Figure 1 shows, these authorships split into five different periods with distinctive degrees of internal coherence.

Figure 1 shows a color scale representing the degree of similarity between the authorships registered in the studied years. The scale goes from the most similar (0, green) to the most dissimilar (1, white). Different shades of blue represent the points in between. Detected periods appear on the upper right side. The same color criteria allow one to portray the periods' inner coherence in terms of authorship and compare them to the other resulting

[1] To do so, we have extracted a list of the main institutional ascriptions from the complete addresses (C1) available in our database. There, we limited our analysis to the first 15,000 most recurrent addresses. We then sorted them alphabetically and proceeded with the semiautomatic construction of a dictionary of equivalences. After detecting semantic regularities in the addresses we used a manual validation process. In this process, we have identified and standardized the names of the main institutions—scientific and, above all, of the Mexican health system—detected in our database. Likewise, the dictionary has been cleaned to reduce the possibility of duplication in the detections and to avoid false positives in the detection of these institutions. In cases of relevant organizations of the Mexican health system, we have proceeded to an expansion of terms detecting recurrent variations that were not part of the first list. For the institutions of the scientific system, priority has been given to the highest level of institutional aggregation; in the case of medical institutions, priority has been given to institutes and specialty hospitals as the unit of analysis. In the case of national public health organizations (IMMS, ISSSTE, SSA, etc.) the different clinics and establishments have been grouped under a single category.

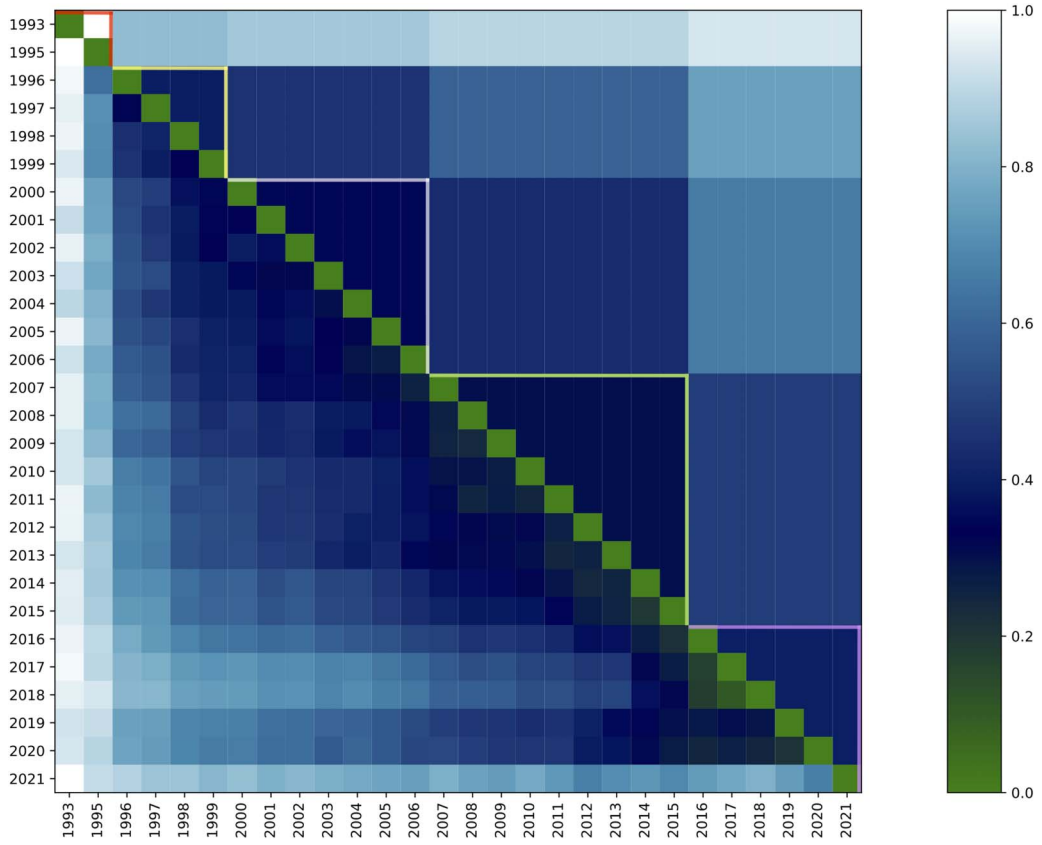

Figure 1. Period detection based on authorships recurrence between 1993 and 2021.

periods. An additional color code has been included for each of them to identify detected periods more easily.

Our analysis has allowed us to access the internal correspondence of authorships within each period and compare the periods between them. Hence, first, we can assess how recurrent authorships are inside each detected period; and second, we can know how much each detected period resembles the others. The resemblance in the yearly authorship structure is valuable information for understanding how cohorts of researchers evolve. The activity of authors with more than 35 documents published between 1993 and 2021 can be divided into five different periods. Between 1993 and 1995 (0.98; indicated by red), authorships show a brief and loosely connected first period. Authors active during these years tend to lessen their participation over time.

A second one goes from 1996 to 1999 and shows a firm and robust structure (0.39; yellow). Authors active in these years, especially in 1998 and 1999, continue to publish in the third period (2000–2006; 0.34; white)—nevertheless, researchers active between 1996 and 2006 notoriously lose prominence after 2007.

The fourth period (2007–2015; 0.3; green) has the strongest resemblance of authorships. It is also the longest of the detected periods, with a total length of 8 years. The last one (2016–2021; 0.4; purple) has a complex structure. First, many of the researchers active in past years will not register papers in 2017 and 2018. Second, it shows the emergence of a new cohort of authorships from 2016 onward.

Figure 1 has allowed us to map three critical breaks in the authorship structure and, hence, in the cohorts of professionals active in Mexican medical research. In 1996, a new generation of scientists became involved in the field. Those researchers started to leave and lessen their participation in 2007, where authors already active in former years welcomed newcomers to the field. Finally, from 2016 and on, a new group of scientists rapidly arose as critical players in medical research in Mexico.

4.2. Overall Thematic Features

A semantic description of the leading research topics developed by Mexican medical researchers between 1993 and 2021 is available in Figure 2[2]. The overall structural organization of the terms co-occurrence network can be analyzed by stressing four different areas of the resulting map. The first one, consisting of [C1] and [C2], shows strong connections between these two clusters. *[C1] Bacillus subtilis & Escherichia coli* (11,876 documents, 21%), reports on research about specific pathogens (*Candida albicans*, *Staphylococcus aureus*, *Escherichia coli*, etc.) and antibacterial activity. The other, *[C2] cancer cells & cell proliferation* (7,641 documents, 14%), deals with genetic research related to cancer investigation. It mostly provides evidence on the biological basis that allowed the identification of cancer cells in different expressions.

On the upper side of the network, we find *[C3] male Wistar rats & brain regions* (8,308 documents, 15%). This cluster grasps a research line oriented to the experimental investigations done using laboratory rats (Wistar rats) to study the brain and neurodegenerative diseases.

Opposed to [C1] and [C2] it is *[C4] Mexican Patients & risk factors* (19,492 documents, 35%). Here, we find mostly clinical, epidemiological research and statistical analysis that allows us to understand the characteristic of the Mexican population and the distribution of specific pathologies (diabetes mellitus, lung cancer, mental disorders, tract infections, gastric cancer, etc.). Reports on clinical trials and case-control studies are normally used to compare drugs, medical procedures, devices, and other treatments. This cluster shows connections to two other clusters: *[C5] HPV infection & human papillomavirus* (932 documents, 2%), a cluster that mostly grasps research on cervical and prostate cancers and their causes; and *[C8] breast cancer & breast cancer patients* (735 documents, 1%). [C8] shows the relevance of breast cancer research and its uniqueness, which stands apart from other research interests. Nevertheless, its strong relation to [C4] shows that the research is mostly patient-based and epidemiological.

At the lower corner of our graph, there is *[C7] T lymphocytes & dendritic cells* (3,017 documents, 5%). This cluster allows for identifying research on cellular characterization concerning the immune response and the immune system reaction to antigens and microorganisms. It is related mostly to cancer research. Finally, a poorly connected cluster, *[C6] DNA repair & DNA damage* (204 documents, 0.4%), points to the study of DNA repair pathways. The overall structure of the network shows very differentiated research areas that seem loosely connected, indicating an essential specialization of Medical research in Mexico. Surprisingly, none of the main diseases reported in ENASEM in 2012 and 2018 appear as the main areas of research in Mexico (INEGI, 2018).

[2] An interactive version of this map is available here: https://documents.cortext.net/lib/mapexplorer/explorerjs.html?file=https://assets.cortext.net/docs/bdf3eeec1206b569a31f173258493397#. Cluster labels have been curated and may differ in the interactive version of this mapping.

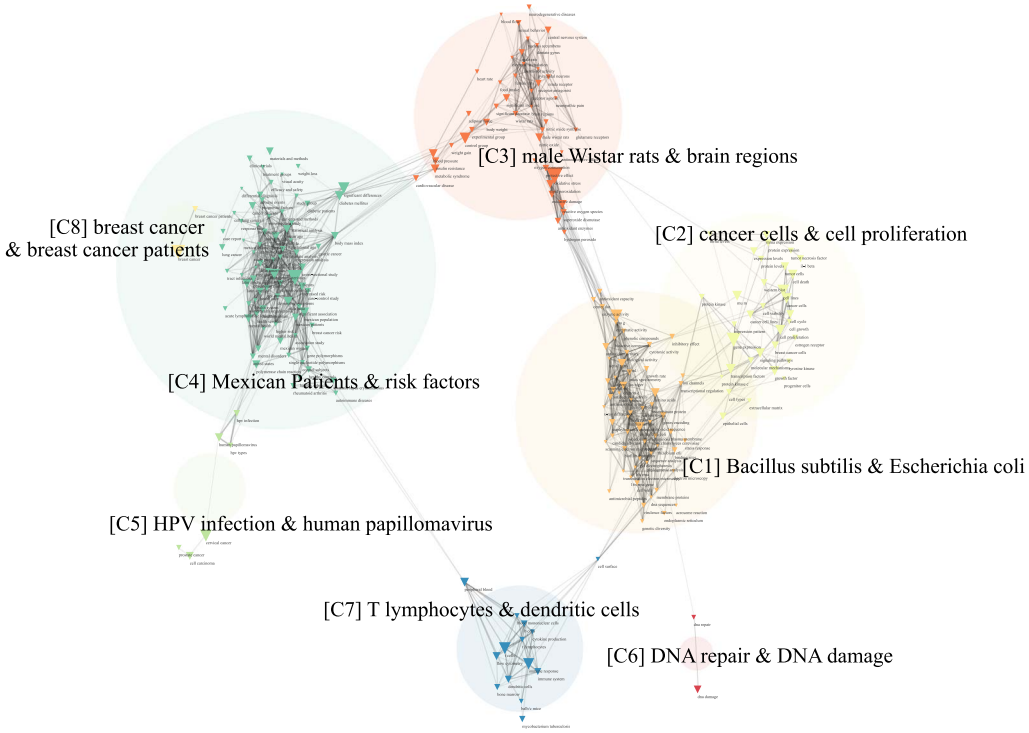

Figure 2. Terms co-occurrence network describing semantic features of medical research conducted in Mexico from 1993 to 2021.

4.3. Institutional Network of Authorships

Detected patterns of institutional collaboration are plotted in Figure 3[3]. There, we have found four different communities that detect how different research facilities, from Mexico and the rest of the world, collaborate in knowledge production activities. At first look, our mapping shows two macrogroups of institutions. The first one and most prominent in terms of documents is *[AD4] IPN & UNAM* (44,271 documents). This cluster is composed mainly of Mexican HEI. The three most notable are the National Autonomous University of Mexico (UNAM), the National Polytechnic Institute (IPN), and the Center for Advanced Research (CINVESTAV), all federal institutions.

Most of the public universities from other States of the Republic are grouped in this cluster, such as the National Autonomous University of Nuevo Leon (UANL), the University of Guadalajara (UDG), and the Autonomous University of San Luis Potosí (UASLP). Private institutions are also relevant to this group, such as the Technological Institute of Monterrey (ITESM) and the Anahuac University. Most of the National Health Institutes are part of this cluster, such as the National Institute of Pediatrics (I. N. de Pediatría), of Neurology (I. N. Neurología y Neurocirugía), and of Cancer Research (I. N. Cancerología). National Health Institutes serve as specialized health institutions that belong to a network of highly specialized hospitals that provide third-level medical care in specific medical specialties. These institutions are also devoted to scientific research and training new specialists.

[3] An interactive version of this map is available here: https://documents.cortext.net/lib/mapexplorer/explorerjs.html?file=https://assets.cortext.net/docs/a5d69ac27748b6cb27c247c4bfa7ef00. Cluster labels have been curated and may differ in the interactive version of this mapping.

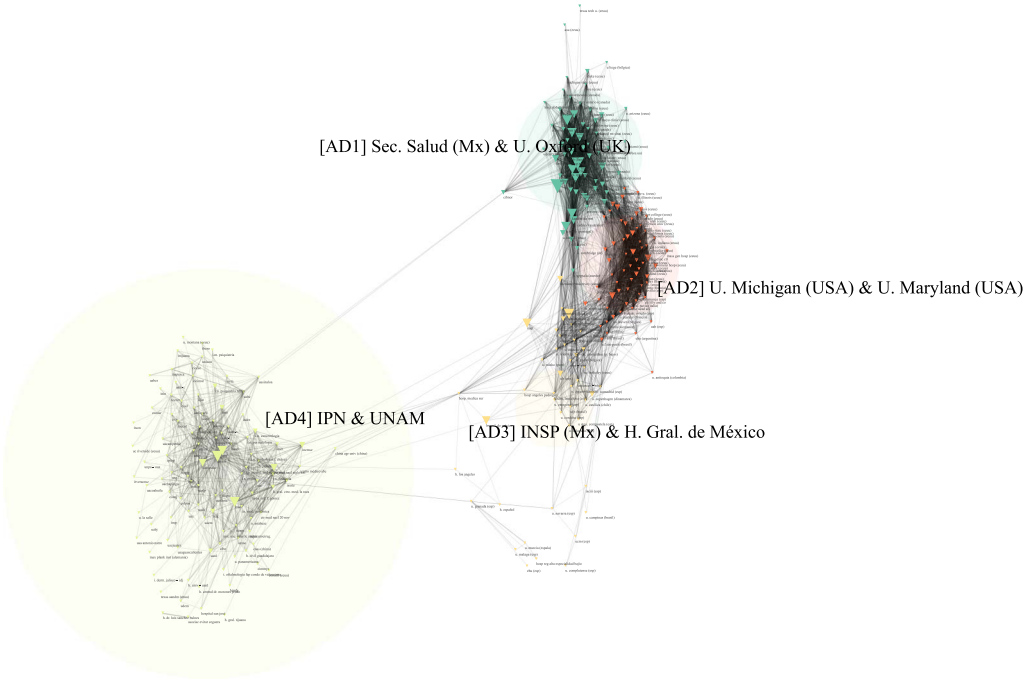

Figure 3. Institutional collaborations in medical research in Mexico from 1992 to 2021.

Other important health institutions, such as the Centro Médico Siglo XXI (part of IMSS) or Hospital 20 de Noviembre (part of ISSSTE) are also part of this cluster. The cluster [AD4] can be interpreted as highly oriented towards scientific research in connection to the Mexican scientific institutions.

Three other clusters, *[AD1] Sec. Salud (Mx) & U. Oxford (UK)* (2,684 documents, 5%), *[AD2] U. Michigan (USA) & U. Maryland (USA)* (3,013 documents, 5%), and *[AD3] INSP (Mx) & H. Gral. CDMX* (2,108 documents, 5%) form another macrogroup that stresses collaboration with international research facilities. There, [AD1] stands out for collaboration with prestigious universities such as Oxford (United Kingdom), Harvard (United States), or King's College (United Kingdom). The most relevant Mexican institution is the Secretariat of Health (SSA), followed by the Northwestern Center for Biological Research (CIBNOR).

Meanwhile, [AD3] shows the strong collaboration of many European universities with researchers from the National Public Health Institute (INSP), an institute mostly related to public health from an epidemiological perspective. The Children's Hospital of Boston (United States) is also a relevant institution but is mostly connected to the General Hospital of Mexico (Hospital General de México) and other foreign institutions. The General Hospital of Mexico falls under the administration of the Secretariat of Health and employs a wide range of specialists. The same situation can be observed in [AD2], where universities from the United States (UCSF, University of Texas, University of Michigan), European national research institutions (CNRS, from France; CSIC, from Spain) are strongly related, mostly among each other.

In general, these three clusters—AD1, AD2, and AD3—show how strongly connected international institutions are to each other. It seems to be the case here that these clusters show a number of very internationalized research efforts. Many different parties take part in international collaboration networks, where papers gain a lot of different signatures of participant

researchers. There, Mexican collaboration competes with the active participation of international researchers. The presence of clusters with such substantial participation is not an indication that no Mexican institution is participating in research efforts with these foreign research centers; it is signaling that their participation is not relevant enough to be worth mapping.

4.4. Thematic and Institutional Co-Occurrences

We have established different thematic orientations within Mexican medical research and found the most relevant collaborations between institutions. In Figure 4, we have put these findings in relation to each other. By bringing these two sets of entities together, it is now possible to see two nonhomogeneous communities. The first one relates public Higher Education Institutions in [AD4] to topical groups in [C1], [C2], [C3], [C7], and [C6], all clusters relatively connected that can be spotted on the right-hand side in Figure 2. These clusters, which deal with topics related to genetics, microbiology, and experimental procedures, point towards a set of specific infrastructure such as laboratories, equipment, and support from research staff.

On the other hand, another community is detected between the institutions from [AD2], [AD3], and [AD1] and the thematic clusters [C4], [C5], and [C8] which lie on the left-hand side of Figure 2. These clusters are mostly related to epidemiological research. From this, it is possible to say that research done by Mexican researchers who are not connected to HEIs tends to lean towards these kinds of subjects.

4.5. Evolution Over Time

So far, we have shared some structural features concerning authorships, on an individual and institutional level, and the thematic features of Mexican medical research. Results have shown that a particular group of institutions has pushed forward specific agendas. What is still missing

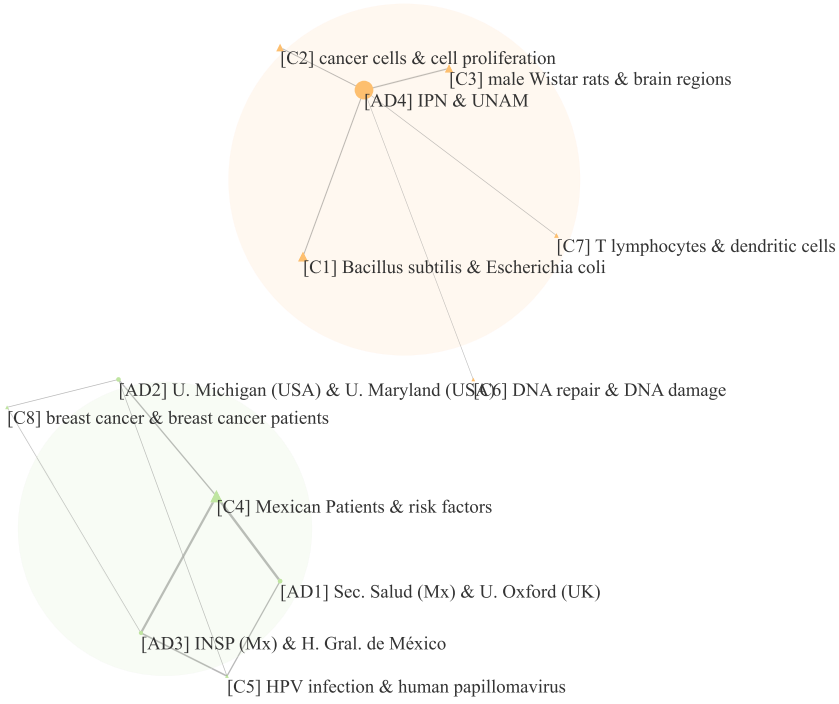

Figure 4. Network of co-occurrence of institutional and thematic clusters.

is to understand if these thematic and thematic-institutional structures have a steady or dynamic behavior during our studied period.

In Figure 5, we present the evolution of the proportional distribution of each of the thematic clusters through the detected period based on authorships' evolution. This analysis demonstrates two things. First, it shows whether a cluster has varied in size against the other clusters detected in our corpus. Second, and connected to the first, it allows us to evaluate the evolution of the relevance (volume-wise) of each of the thematic areas that describe medical research in Mexico. The results are consistent with the structural analysis resulting from Figure 1. The first change in the authorship structure, detected from 1996 on, relates to the beginning of an increased relevance for [C4], related to the description of the orientation of Mexican population towards specific diseases.

We also spotted a cohort of authors reducing their participation in research from 2007 onwards, also detecting the second wave of newcomers. This shift also has implications regarding the thematic structure of the scientific papers and the knowledge they produce. We not only observe a second increase of [C4]'s importance, but the cluster related to neurological experimentation with laboratory rats, [C3], starts to lose relevance slightly. This trend is confirmed as this cluster loses more volume and finally concedes its third place in relevance to [C2]. Then, it seems safe to assume that a significant proportion of the authors that have lessened their research activity during this last period relate to [C1] and [C3], both topics that were more relevant at the beginning of the examination period. Also, the group of newcomers detected from 2016 on appears to be related to cellular [C1] and epidemiological research [C4].

Finally, Figure 6 is a good complement of the former analysis as it allows one to understand how institutional and thematic clusters have developed over time. Results show the growing importance of Mexican medical research of health institutions and epidemiological research. This points towards an acceleration in the transformations in the orientation of research done in Mexico on medical-related issues. Given the structure of this transformation, it is safe to assume that many of the late newcomers—from 2016 on—relate to these health institutions

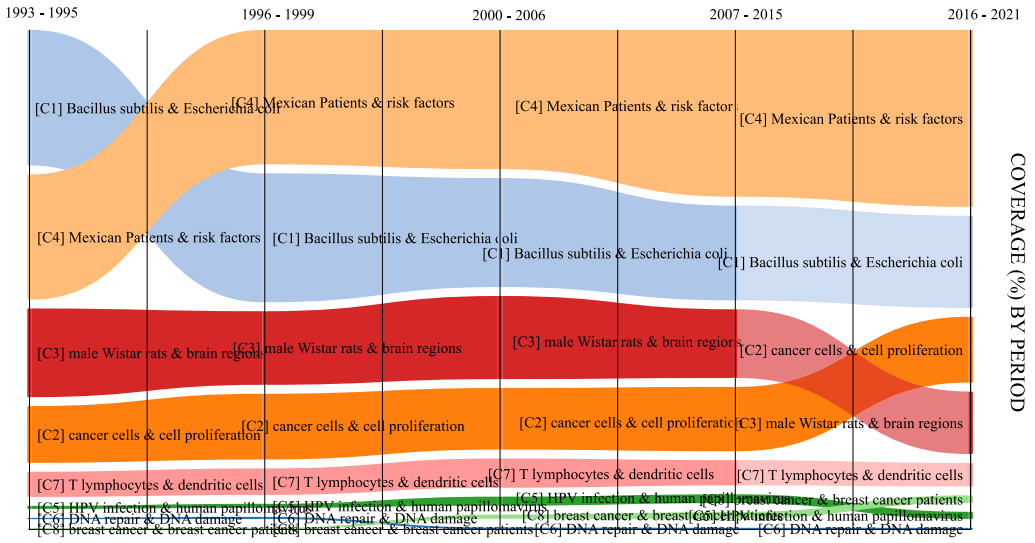

Figure 5. Evolution of the proportional weight of documents corresponding to each of the thematic clusters in the detected time periods.

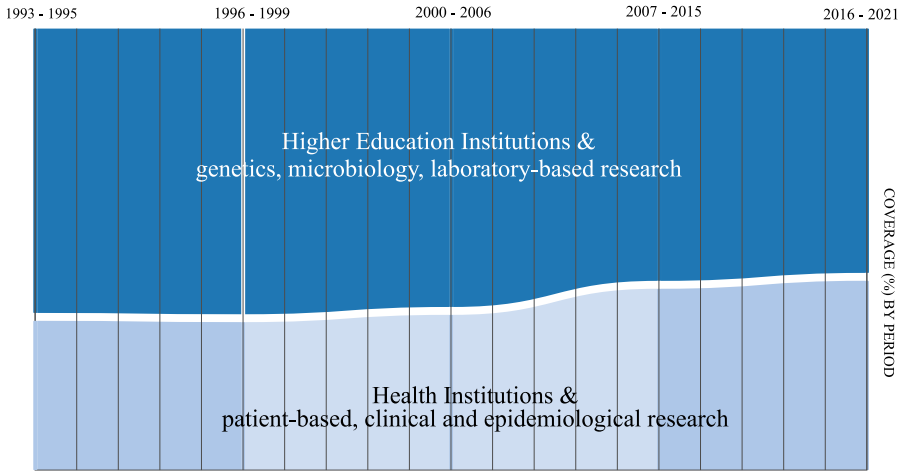

Figure 6. Evolution of the proportional weight of the co-occurrences of institutional and thematic clusters in each of the detected time periods.

and their international partners. This points to an acceleration in the transformations in the orientation of research done in Mexico on medical-related issues.

5. DISCUSSION

This paper has shown features of medical research published between 1993 and 2021 in Mexico, a nonhegemonic country in the world scientific arena. We have taken a particular interest in authorships. They offer a way of understanding the accumulation rhythms in research capabilities, a salient trait in science policy implemented in the country during the last 30 years. We have been able to map significant breaks in the authorship structure. Three of them arise as critical movements, starting in 1996, 2007, and, finally, in 2016. They all point towards meaningful changes in who is conducting and publishing research, but they unfold in different ways.

Following Biagioli and Galison (2003), we have interpreted these authorships as a result of a coproduction between junior and senior researchers. In 1996, a new generation rose suddenly, but it was not long before they started languishing. They seem to be trailblazers of medical research in their institutions. This new generation of researchers could be stimulated from the Programa de Apoyo a la Ciencia en Mexico (PACIME), the first World Bank loan dedicated to strengthening S&T in Mexico (González-Brambila & Veloso, 2007), considering that training of researchers takes around 5 years. This decline draws an interesting contrast. What we have identified as the second grand wave of newcomers erupts swiftly from 2007 on, with many of them active and publishing before that date.

The data from authors who consolidated their relevance from 2007 on is consistent with the profile of junior researchers advancing their careers. This coincides with the drop in federal science and technology expenditure as a percentage of GDP, which gradually descends from 0.42 in 2000 to 0.32 in 2007 (CONACYT, 2010). Moreover, as this analysis has shown, the consolidation of this cohort goes along with a shift in the thematic profile of published research as shown in Figure 5.

In contrast, from 2016 and on, a new cohort of medical researchers rapidly gained numbers and importance in publications with Mexican signatures. Because few authorships of these

new researchers show activity in the early years of the studied periods, we can assume that this is a new group of newcomers. In 2016, the number of people classified as part of the stock of human resources in S&T increased 20.3%, in comparison to the previous year (CONACYT & SIICYT, 2016). Moreover, the number of researchers accepted in the SNI in health sciences increased 13% from 2015 to 2016, and 12.3% from 2016 to 2017 (CONACYT & SIICYT, 2018a).

Interesting findings arise as we look at these changes through the lenses of the thematic and institutional structure of Mexican medical research. Overall, the eight topical domains from the studied documents—Figure 2—can be organized into two clear macrogroups, as the correspondence between thematic and institutional clusters has shown in Figure 3. One group appears strongly connected to data gathered during everyday work with patients, so we have chosen to call it *patient based*. Notoriously, these sets of concerns appear firmly linked with public institutions such as the General Hospital of Mexico and the Mexican Secretariat of Health (SSA). Both institutions are devoted to nonspecialized health services and conducting primarily clinical and epidemiological research in strong collaboration with a large group of international institutions.

Research produced using more sophisticated techniques—as in genetics, microbiology, immunology, or neurodegenerative diseases—appears strongly connected to a vast array of HEIs and specialty hospitals. This sort of experimental research arises in strong connection with a kind of research that we have called *laboratory based*. Here, the availability of infrastructure, resources, and previous experience is a crucial element. In contrast to other detected dynamics involving international collaborations, we have found that HEIs based in Mexico City, such as UNAM, IPN, or CINVESTAV, provide leadership to institutions in other states of the Republic. The role of these organizations in setting and consolidating a medical research agenda is noteworthy. These findings[4], when contrasted with claims made about the subordinated integration (Kreimer, 2006) help differentiate ways of integrating into the international arena within the Mexican medical landscape. Because national HEIs and specialty hospitals lie at the center of their collaboration clusters, laboratory-based research appears with a higher negotiation margin when building their research agendas than patient-based research lines.

We have noted a growing gap between research conducted in health institutions and scientific ones, pointing towards a historical pattern of specialization in medical research in Mexico. Over the years, patient-based research has steadily increased its proportional volume compared with other research lines. As the distance between both detected branches of research seems to be widening, it seems hard to validate the existing assumption in the international community of physicians that a greater number of research-focused doctors will help translate research into practice (DeMaria, 2003; Wyngaarden, 1979). Moreover, this research has stronger collaboration ties with institutions from the Global North than with Mexican ones. Hence, these changes signal a specific profile in the rising participation of Mexican researchers in transnational research efforts, one that leans primarily on patient information.

The diminishing importance of laboratory-based research lessens the significance of institutions that train new physicians and active members of the Mexican scientific system (i.e.,

[4] Our methodological approach has prioritized a national scale. This means that larger patterns of the international collaboration structures cannot be captured. Hence, as our database is not built around a specific drug, pathogen, or disease (Levin, Kreimer, & Jensen, 2021), we are only able to compare the importance of international collaboration between the different detected topics.

HEIs and specialty hospitals). Along with this change, the ability to define and deploy research agendas on a national level by big Mexican HEIs such as UNAM and IPN seems challenged. This rising specialization pattern comes as a critical finding to inform the management of STI efforts, especially if those are set to tackle issues of national relevance.

6. CONCLUSIONS

This article's main objective has been to describe and understand the structural features of scientific communities producing knowledge in medicine and health sciences in Mexico by looking at emergent traits of its scientific production. This paper has shed light on the relations between publishing authors, semantic clusters, and collaboration structures. It has shown, to some extent, crucial and emergent structural features that mediate knowledge production in an increasingly relevant area as medicine in a nonhegemonic country such as Mexico.

We have detected different styles in collaboration structures. Styles that correlate to the historical structure drawn by trained and active researchers and the overall thematic orientation of research. A laboratory-based kind of research arises, performed by scientists working at HEIs and specialty hospitals. Our data demonstrate that these scientists have longer careers and seem to be losing prominence in medical research in Mexico. Still, they appear to have a higher negotiation margin in their research agendas when compared to the other detected style, which we have called *patient-based research*.

Patient-based medical science shows a contrasting portrait. Strong links with international scientific consortia point to a limited possibility of directing research. These Mexican medical researchers appear in our analysis as a recent and fast-growing cohort, strongly connected to health system institutions. There, official strategies were put in place by the national administration and promoted from 2013 on the development of bioethics commissions, on both national and state levels (SSN, 2013, p. 64). They also endorsed the creation of bioethical committees in public hospitals, establishing the necessary conditions for Mexican researchers in health institutions to partake in global biomedicine and biomedical research efforts.

The unbalanced nature of the collaboration networks casts a shadow over the opportunities that these research-focused specialists have for doing translational research. The influence of institutions not primarily devoted to scientific and educational matters on a national research landscape is an important takeaway of these results. In future research, more of this can be learned by analyzing the diversity of collaboration and relating it to impact, using citations as a measure of impact.

In our findings, specific international collaborations arise as a crucial dimension for understanding the evolution of medical research in Mexico. Nevertheless, this seems to remain a lightly addressed matter in national planning (SSN, 2013, 2020). Our paper brings forward important evidence to discuss the limits that science policy and priority setting can have in a national scenario. These results highlight the selective influence that certain international linkages can have in national scenarios, limiting the reach of national policy to define either research topics or partners. This research provides evidence that can be of use to inform future policy efforts on the subject.

In Mexico, even though researchers in medicine and health sciences have taken different positions, most of them work for academic institutions (CONACYT & SIICYT, 2018b). It is important to note that academic institutions do not have hospitals or provide healthcare services, and thus there is a division between those who mainly do research and those who focus mainly on healthcare services. Unfortunately, there is no relevant information regarding

federal expenditure dedicated to research in medicine and health sciences. It would be of interest to have an estimate of the average cost of each published paper over time and in each of the detected clusters of knowledge. Also, it would be desirable to deeply analyze the most prevalent issues in each thematic cluster.

It remains relevant to know if other areas with an important state-led service infrastructure, such as agriculture or energy research, have similar publication patterns for the Mexican case. An outline and comparison of these structural features in different areas of research would have meaningful implications for science policy and institutional research strategies.

Also, future research can profit significantly from data triangulation with institutional data sources, such as the one from SNI, which would help to better understand the role that incentives for research productivity have had in steering the trends found here.

This study has focused on a set of the most relevant authors to explore the temporal structure research capabilities. These researchers, as stated above, are signers or cosigners of 62% of the analyzed documents. Nevertheless, this approach has a couple of limitations. First, the informed lack of normalization in signatures especially affects some groups among the studied authors. As explained, the lack of normalization seems to be more common in health institutions and in Mexican organizations. Hence, this bias toward normalized authors' names could mean that some groups are overrepresented in our study of authorship cohorts.

Also, as it stresses a bias towards the most productive authors, this work somehow downsizes the relevance of less productive authors and diminishes their role in sustaining the scientific effort described here. Then, a more detailed characterization of the documents published by these less-productive authors would be extremely helpful in ascertaining their role in the historical pattern of specialization detected here. Where is the work? What do they research? With whom do they publish? Future research can be devised to specifically address this topic.

Our findings report these transformations mostly in a descriptive manner. Hence, there is much to gain in future qualitative research informed by these findings. A round of interviews with members of the identified communities can be of great help in validating and expanding the findings on the structural evolution of medical research in Mexico.

Research of this type generates information that could be useful for policymakers to identify key elements for the design of institutional and government strategies for improving the health of the ecosystem in Mexico. Thus, this paper contributes with key insights and methods, and provides tools for informing the evolution and transformation of medical research in Mexico.

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AUTHOR CONTRIBUTIONS

Matías Federico Milia: Conceptualization, Data curation, Formal Analysis. Investigation, Methodology, Software, Visualization, Writing—original draft, Writing—review & editing. Claudia Gonzalez Brambila: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing—review & editing. Ángel Lee: Supervision, Validation, Writing—review & editing, José Ignacio Ponce: Data curation, Investigation, Resources, Validation, Writing—review & editing.

COMPETING INTERESTS

The authors have no competing interests.

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DATA AVAILABILITY

Data are publicly accessible on the Open ICPSR repository (Milia et al., 2022).

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