Innovation in the global medtech industry: An empirical analysis of patent applications, 1960–2014*

Pierre-Yves Donzé† and Raphaël Imer‡

Abstract

This article uses a quantitative analysis of patent applications to shed light on the dynamics of the global medtech industry between 1960 and 2014. It demonstrates the existence of three types of innovative companies that maintained their competitiveness over time: large multinationals in the electronics industry, large specialized medtech companies arising from mergers between startups; and traditional specialized SMEs. Moreover, the research illustrates the disappearance of non-specialized manufacturing firms after the integration of electronics in the 1970s.

JEL classification: L60, N60, O31, O34

Keywords: Innovation; medtech industry; patents; Japan; United States; Switzerland; Germany.

1. Introduction

The medical instrument and device (hereinafter "medtech") industry is today a large, fast-growing business around the world. The consulting company Frost & Sullivan estimated the industry's revenues at more than 370 billion USD in 2017 (Frost & Sullivan, 2017), a massive total relative to the same value in 2000—only 169 billion USD (Panescu 2006). Developing mostly after World War II, the medtech industry emerged with the development and production of pacemakers and artificial implants during the 1950s and 1960s, grew on the basis of medical imaging equipment and the integration of electronics in the 1970s and 1980s, and then incorporated information and communication technology (ICT) in the 1990s and thereafter (Panescu 2006). Data on the US market captures the rapid growth since the late 1980s: the value of shipments for medical equipment and supplies in America went from 2.9 billion USD in 1960 to 4.3 billion in 1970, 13.3 billion in 1980, 34.5 billion in 1990, and 58.4 billion in 2000 (Census of Manufacturers, 2018).

This booming expansion has resulted from both the increase of healthcare expenses, which represent a major incentive for medtech companies, and a high level of investment in research and development (R&D). In the United States in 2002, the medtech industry had one of the highest proportions of R&D

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† Professor at Osaka University, Graduate School of Economics.

‡ Senior patent analyst at Centredoc, Neuchâtel (Switzerland).

to gross sales (11.4%), second only to the pharmaceutical industry (12.9%) but far higher than the automotive (4.1%), electronics (3.9%), and aerospace-defense (3.1%) industries (Panescu, 2006). It thus stands as a high value-added industry, an attractive target for future economic growth policies for most of governments in developed countries (Foray, 2014).

Despite this economic and technological significance, however, the medtech industry remains largely unknown. The question of who carries out innovation is a major piece in properly understanding the dynamics of the industry—but the lack of studies on a global scale makes the corresponding answer hard to come by. R&D in the medtech industry involves a broad variety of actors, ranging from medical doctors, engineers, and mechanics to startups, government agencies, universities, small family firms, and large multinationals. Some scholars have demonstrated a trend toward concentration in the industry. According to Kruger & Kruger (2012, p. 437), the concentration ratio in the global medtech industry (the market share controlled by the top 10 companies) went from 45% in 1995 to 62% in 2009. Since the 1990s, M&A efforts have enabled the largest companies to strengthen their dominance. Still, the medtech industry is a truly diverse sector that includes a broad range of actors. The ranking of the top 100 largest medtech companies around the world in 2014, according to the American magazine *Medical Design & Outsourcing*, is home to large corporations like Medtronic (92,000 employees) and Boston Scientific (25,000 employees) but also numerous startups (e.g. Insulet, 650 employees) and university spin-offs (e.g. Abiomed, 150 employees) (*Medical Design & Outsourcing* 2016).

A second characteristic is the overwhelming domination of this industry by US companies, with Japanese and German firms, along with a handful of companies from other European countries, far behind. *Medical Design & Outsourcing*'s ranking of the top 100 largest companies includes a total of 57 companies from the United States. The second highest-ranking nation is Japan, with only 15 companies, and the third Germany, at 6 firms. Other countries have fewer than 5 firms. Moreover, in the United States, the medtech industry is clustered in a few large urban states and cities with competitive universities and R&D research facilities, like California, Boston, New York, Massachusetts, Illinois, and Minnesota (Clayton Matthews 2001).

Consequently, the diversity of actors makes it difficult to attain a general, comprehensive view of the conditions of innovation in this high-tech industry and the evolution of these conditions over time. Much of the existing research focuses on specific actors (medical doctors, small firms, large corporations, and universities), specific countries, or specific regions (see the literature review below). Without a knowledge of the global medtech industry, though, gauging the significance of each individual work can be a challenge. The objective of this article is thus to offer an exploratory analysis of the dynamics of the industry around the world, drawing on an analysis of patent applications. The main research questions addressed in this article are: Who are the most important innovators in the medtech industry? How have the dynamics of innovation changed over time? What kinds of firms dominate innovation? When and how did universities establish themselves as major innovators? To answer these questions, we use a quantitative analysis of patent applications. As primary sources, patents appear frequently in economics and economic history for the purposes of estimating the level of innovation of a firm or a country (Cantwell 1995, Chang 2001, and Fontana, Nuvolari, Shimizu & Vezzulli 2013). We focus here on patent applications for medtech innovations (IPC code A61B) by individuals and organizations between 1960 and 2014 in the United States, Japan, Germany, and Switzerland. The paper includes six sections. Sections 2 and 3 present a pertinent literature review and the study's methodology, respectively. Next, section 4 explains the analysis data and the main results. Based on those findings, section 5 gives a more qualitative analysis and establishes some models of innovation. Finally, section 6 discusses the results and concludes the paper.

Box 1: Defining the medtech industry

The "medtech industry" includes such a broad range of products that its definition varies according to the criteria that analysists, consultants, and scholars adopt. Moreover, the evolution of innovation since the 1960s has had an impact on the boundaries of this industry, especially with the advent of electronics and ICT. A restrictive definition encompasses only instruments and devices but excludes medical imaging equipment and healthcare IT (e.g. Frost & Sullivan 2017). In the United States, the Census of Manufacturers does not include ophthalmic products. As for academic researchers, most do not define the "medtech industry" explicitly. However, the prevailing approach is not to include pharmaceutical goods. Drugs and medicines belong to another industry, with (mostly) different actors, although the goods sell in the same market. Moreover, the recent advent of biotechnology challenges the differentiation between "medtech" and "pharma," as drugs and devices tend to become more and more integrated.

Two general and internationally accepted indicators help establish a proper definition of the "medtech industry." First, the Standard Industrial Classification (SIC) identifies industries with a four-digit code. Category 384 includes "Surgical, Medical, and Dental Instruments and Supplies," with five codes (3841, 3842, 3843, 3844 and 3845). Second, the International Patent Classification (IPC) has a code (A61) for "Medical or Veterinary Science; Hygiene." The category is broad, including products for dental hygiene, drugs, transportation devices, etc. For this study, we use subcategory A61B for "Diagnosis, Surgery, Identification," which represents the core of the medtech industry and includes all its major actors.

2. Literature review

Although the medtech industry has attracted the attention of numerous scholars in management, economics, and business history, there is a lack of studies on the global scale. The general dynamics of the sector thus remain largely unknown, unlike other high-tech industries such as electronics, ICT, and automobiles. Works on the medtech industry tend to fall into four general categories.

The domination of multinational enterprises

The presence of large global companies is a major characteristic of the medtech industry. For example, Maresova & Kuca (2014) showed that the ten largest firms in the sector accumulated revenues of more than 7 billion USD in 2012 and 2013. Two types of explanations help clarify this feature. First, some economists have argued that, on the basis of research on X-ray and electromedical equipment, a handful of multinational enterprises has dominated the industry since the interwar years due to continuous and accumulated investments in core technology. Gelijns and Rosenberg (1999) emphasized the first-mover advantage as a major determinant. They have also showed that path-dependency investments in innovation have strengthened the positions of large multinationals. Focusing on the example of Johnson & Johnson, Christensen & Raynor (2013) argued that these big firms were able to overcome the so-called "innovator's dilemma" (Christensen 2013) through the acquisition of disruptive startups.

Second, several scholars have found that large medtech firms result largely from waves of mergers and acquisitions (M&A), another important feature of the industry. With the high-margin, high-growth-potential nature of its business, medtech attracts newcomers from low-growth manufacturing sectors that reorient their resources. Usually, these types of companies enter the medtech industry through the acquisition of small companies specializing in simple devices and then use their own technological resources to upgrade the equipment (Lawyer & Alford 2005). Representative cases include Tyco International and its subsidiary Tyco Healthcare Group (Covidien since 2007), Danaher Co., OSI Systems Inc., and Smiths Group PLC. According to Boston Consulting Group, the number of medtech companies with more than one billion USD in gross sales went from 23 in 1994 to 37 in 2004 (Lawyer & Alford 2005). However, new entrants' diversification toward medical devices is not the only cause of growth among medtech firms. Some medtech companies also developed through diversification within the industry. Wu (2013) tackled the case of the US cardiovascular medical device industry since 1976 and showed that firms used their technological capabilities for product diversification in order to cope with changes in demand.

Clusters of SMEs and spin-off chains

Besides the presence a few large companies, the existence of numerous small and medium-sized enterprises (SMEs) is another specificity of the medtech industry that has drawn substantial attention among researchers. Moreover, medtech SMEs tend to gather in regional clusters throughout the world, owing to the industry's "long value chain [that requires] different competencies and is highly innovative" (Steinle et al. 2007). According to Shaw (1998), a consequence of such an industrial structure is the potential for innovation via a learning process between various actors (entrepreneurs, doctors, patients, etc.). That constitution leads to an endless innovation process (development, purchase, feedback, re-innovation, diffusion of new innovation, etc.), benefiting from a dense network of actors.

Most of the medtech clusters that have been subject to scholarly investigations are organized on a national, sometimes regional, level (Clayton Matthews 2001, Burfitt e.a. 2007). In Germany, for example, Steinle e.a. (2007) considered the national medtech industry as a single cluster with more than 100 actors (enterprises, universities, research centers, etc.) in the mid-2000s, of which almost 60% formed after 1990. That German cluster also carries out its own innovation and does not depend on outsiders for technology; on the contrary, it attracts US multinational enterprises such as GE

Healthcare, which invests in the country to acquire German knowledge. Steinle e.a. (2007) did not, however, consider the global organization of Siemens and its impact on the domestic cluster.

A major characteristic of medtech clusters is the importance of spin-off chains for the creation of new SMEs. In the United States, for example, many employees of large medical device companies (Johnson & Johnson; Medtronic; Boston Scientific; Abbott; St. Jude; etc.) founded their own firm, aiming to develop innovative new ideas. Orange County (California) is a particularly important cluster, sprouting many spin-off chains since the beginnings of the medtech industry (de Vet & Scott 1992). The first important companies appeared during the 1950s, with Bechman Instruments and Edwards Laboratories specializing in mechanical heart valves. Don Shiley, chief engineer at Edwards Laboratories, developed a new artificial heart valve and started his own company in 1963 (Shirley Laboratories). Later, other employees left Edwards to found Bentley Laboratories (1964) and Hancock Laboratories (1967). Then, in the 1970s and 1980s, several shifts in the academic and political environment (the growth of the medical school at the University of California, development of the local airport, and decreases in public spending for defense contracts, for instance) led engineers in electronics to look for new businesses—and medtech was a promising one. Tens of spin-offs launched during these decades. The profitability of such spin-offs in comparison with the respective parent companies where their founders previously worked is an important point to address. Chatterji (2009) used financial data (Dow Jones statistics) to investigate this issue, showing that technology itself was not the sole determinant of profitability of a newly created spin-off. The non-technological knowledge at large companies (e.g. expertise in marketing, regulatory affairs, and the identification of entrepreneurial opportunities) is also a major factor in the creation of a new SME. In the United Kingdom, Craven e.a. (2012) argued that most medtech SMEs are headed by engineers who lack knowledge in management and health economics. That shortcoming has a negative effect in terms of profitability.

Moreover, SMEs in medtech clusters face two major problems. First, access to the global market is difficult due to limited resources. Analyzing the internationalization of German medtech SMEs, Heiss (2017) demonstrated that firms essentially focused on the domestic and European markets but underrepresented in overseas markets and emerging countries. This weakness is one of the reasons behind takeovers by large multinational enterprises that have the resources to provide SMEs' promising technologies with access to the global market. The significant presence of foreign MNEs in a cluster can also benefit the internationalization of local SMEs. That was the case of the French medtech industry, for example, where foreign-owned companies had an 80% share of exports and 75% share of turnover in the early 2010s. Andersson e.a. (2013) showed that, for some SMEs, proximity to foreign MNEs is an opportunity to internationalize through M&A or joint ventures.

Second, the domination of foreign-owned companies in some clusters can also have some negative effects in terms of technological development. When local SMEs become subsidiaries of global firms, going up in the value chain is often a major challenge. In Ireland, the medtech industry centers on manufacturing operations and not R&D because of the considerable weight of foreign MNEs. In 1999, while the share of R&D expenses in the industry averaged 7% of gross sales on a global basis, it was only 1.5% in Ireland (Fennelly & Cormican 2006).

Networks connecting medical doctors and firms

Research on the history of science and technology, as well as studies of the social history of medicine, have demonstrated the major role played by social networks in the adoption of innovations made by medical doctors and small mechanic workshops. Hospitals, medical associations, and manufacturers connect innovators to users and contribute to the diffusion of new devices and techniques (Schlich & Tröhler 2006, Timmermann & Anderson 2006, Rabier 2013). Some scholars have looked beyond the role of individuals and highlighted the growing importance of large companies as innovators since the last decades of the twentieth century, as has been the case in the US breast prostheses industry (Gardner 2000). However, no studies have explored the nature of the relation between medical doctors and large companies in detail. Harrington (1988) showed that, in the 1950s and 1960s, incremental innovation occurred in hospitals and operation rooms, with surgeons developing step-by-step instruments for scoliosis treatment. When the medical procedure reached a stable state, doctors approached a manufacturing company (Zimmer) to standardize and mass-produce instruments and went to academic conferences to publicize the new process. Schlich (2002) demonstrated similar findings through the case of osteosynthesis during the same period. Swiss surgeons used both a manufacturing company and international medical conferences for the diffusion of their innovations.

Cooperation between medical doctors and firms has been also approached through an analysis of patents. Shah & Robinson (2007) have shown that, in the United States, physicians were involved in 19.3% of the patents filed for medical devices between 1990 and 1996; moreover, about 60% of those doctors were physicians in practice (users of technology) but only 14% worked in hospitals. The researchers thus emphasized the importance of involving users (doctors and physicians) in developing medical technology. Chatterji e.a. (2008) argued that patents with physicians as co-applicants are of a better quality in the sense that they have more citations than patents not involving physicians. Donzé (2018) showed that Japanese companies that co-developed medical equipment together with doctors increased their competitiveness against foreign MNEs.

In addition to examining individual doctors, some scholars have investigated the roles of hospitals and universities in medtech clusters. Using the case of Berne in Switzerland, Weigel (2011) concludes that the hospital is "the main functional source of medical device innovation" (p. 43). In particular, hospital physicians play central roles as co-developers of technology, users of devices, and diffusers of innovation. However, technology spin-offs from hospitals are rare in Europe, unlike the United States. For example, the roots of Medtronic, a leading medical device company that started with cardiac and neurological technology, go back to open-heart surgery at the University of Minnesota during the 1950s (Llobrera et al. 2000). Gelijns & Thier (2002), meanwhile, argued that the flows of technology transfers between universities and industry should go in both directions to achieve a high level of innovation in the medtech industry. For the United States, they stressed the key importance of the Bayh–Dole Act (1980), which allows universities to hold patents. But, as Mowery & Rosenberg (1998) and Mowery & Sampat (2001) have emphasized, university and industry relations have a longer history. In particular, the Research Corporation, founded in 1912, was the interface between university research and industry until its decline in the 1980s, precipitated by a new legislative environment (Bayh–Dole Act).

Recent research has also underscored the dangers of overestimating the impact of medical doctors, hospitals, and universities on innovation in the medtech industry. According to Rosenberg (2009), the most important discoveries in medical science since the late nineteenth century actually emerged from areas outside medicine (physics, computer science, and biology) and found applications in medicine, like X-rays in the 1890s. His argument is that institutional innovations (the implementation of medical schools at university campuses) in the United Kingdom and the United States promoted these transfers over academic boundaries. For example, MRI technology was developed by physicists. Medical equipment makers invested in MRI business through the employment of PhDs in physics. The paper does not discuss the corresponding implications for the medtech industry directly, but it shows the importance of connections to research outside medicine. Similarly, Coffano, Foray & Pezzoni (2017) argued, based on the Swiss case, that innovation in the medtech industry benefits considerably from the presence of inventors specializing in complementary technology; in other words, connecting regional clusters to external knowledge is vital. Their regression analysis of patents showed that the presence of academic inventors has not had any particular effect on innovation.

The state and regulation

Finally, the regulation of healthcare has a major impact on innovation and the diffusion of new medical technology (Romeo e.a. 1984, Rossiter & Wilensky 1984, Slade & Anderson 2001). The variety of technical directives and legal frameworks, first of all, has an influence on the organization of the global medtech industry (Estrin 1990 and Teixeira 2013). In the United States, for example, the Food and Drug Administration (FDA) introduced premarket clearance for medtech devices in 1976 after a spate of accidents involving devices such as pacemakers (Panescu 2006). Due to a lack of international standards, companies need organizational capabilities to apply for certification in foreign markets, which can be a hurdle for SMEs (Heiss 2017). Safety regulation is also largely used as a non-tariff barrier by some countries, including Japan. According to Foote & Mitchell (1989), measures adopted by Japanese authorities in the 1970s and 1980s (import approval, price fixing by the Ministry, and non-recognition of foreign safety tests and information) led to a trade deficit for the US medtech industry since the mid-1980s and gave way to an FDI strategy in sectors where American companies had cemented their technological leadership, like pacemakers.

Conclusion

This literature review introduced the most important works related to the medtech industry, its organization, and its conditions of innovation. However, many publications lack a proper historical contextualization—a factor that leads to some apparent contradictions between different studies. The basis of competitiveness for large companies (path-dependency investments or takeovers of innovative SMEs), the nature of relations between SMEs and MNEs, and the roles of medical doctors in innovations are major issues without a consensus in literature. Yet an evolutionist perspective that emphasizes the historical context can offer a general overview of the dynamics of innovation in the global medtech industry since 1960, and that grasp can contribute to a better understanding of the major issues in the literature.

3. Methodology

In order to discuss the dynamics of innovation in the global medtech industry since the 1960s, we built a database of medtech-related patent applications (IPC code A61B) using the worldwide PATSTAT database of the European Patent Office (EPO), which includes some 90 million patents. Information about assignees was added from the EPO worldwide bibliographic database DOCDB.

We identified a total of 521,365 patents and 647,399 assignees (a patent application sometimes mentions more than one assignee) for the period 1960–2014. Next, we identified the nationality of patents on the basis of the place of residency of assignees (mostly enterprises and universities) through the address mentioned on each patent application. If a Japanese company applied for a patent through its German subsidiary, then, the assignee would be considered German. This method has been chosen to enable comparisons of the medtech industry across various countries. The place of earliest application may have been easier to identify, but that data point does not properly reflect the nationality of assignees; after all, many individuals and companies do not apply for patents in their home countries but often directly in the United States or, since the 1980s, to the EPO. In some cases, identifying the place of residency was problematic because the information about applicants, such as their place of residency, is not always available. According to the EPO, the countries of about half of the patents in PATSTAT are unknown. In order to overcome this problem, we used the Patent Standardized Name (PSN) and standardized names of applicants with the KUL algorithm and the Harmonized Applicants Names of the OCDE. Then, we could share the country code through PSN with the same ID. This reduced the rate of patents by applicants from unknown countries considerably; the overall rate comes to just 6.8% of all assignees for the period 1960–2014. Section 4 gives a general overview of the data.

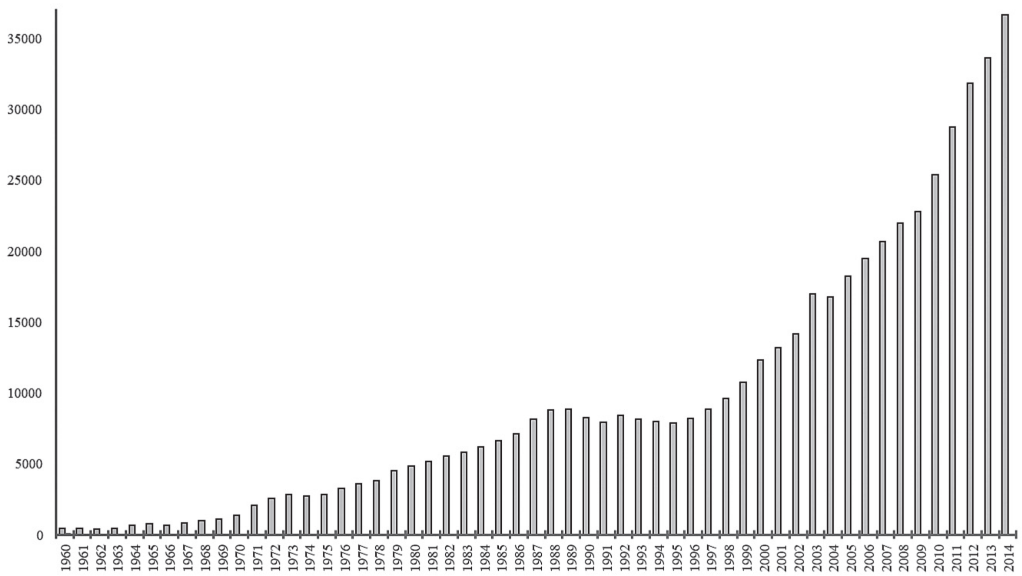
The next step involved focusing on four countries (United States, Japan, Germany and Switzerland) and breaking the data down by decade. The four countries in question were selected because they hold dominant positions in the medtech industry (United States, Japan and Germany) or have qualities representative of many Western European countries (Switzerland). Due to the methodological difficulties of identifying Chinese applicants (challenges in certifying names on the sole basis of the Roman alphabet as provided by the PATSTAT database; late adoption of the IPC system), we did not include China in the detailed survey by country. We manually classified assignees for the four countries into three groups (enterprises, universities and research centers, and individuals). We also added a fourth group (government agencies) for the United States. Section 4 presents the general results of these operations, as well.

Finally, for each of the four countries, we selected the major innovators (the top 20 firms and top 10 individuals with at least 3 patent applications) for each decade and carried out a qualitative analysis to shed light on the evolution of the most important actors of the medtech industry in each country. We identified firms and individuals using patents themselves, of course, as well as a broad range of official (firm registration) and online (LinkedIn) sources that we detail below. The results of the survey appear in section 5.

4. Data and descriptive analysis

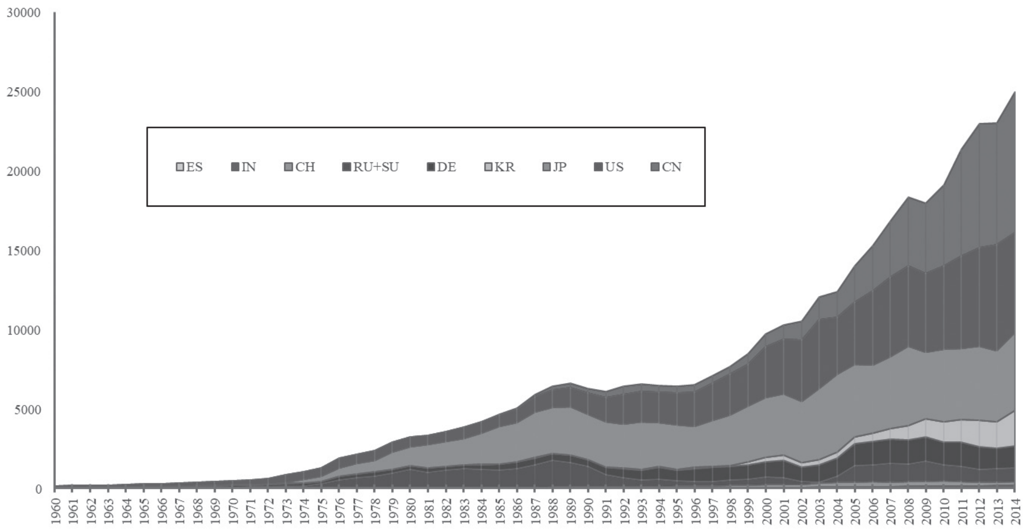
The general evolution of patent applications in the medtech industry (IPC code A61B) between 1960 and 2014 is shown in Figure 1. The cumulative evolution of patent evolution in the most important countries offers additional information that sheds light on the general trends (Figure 2). Table 1 gives data related to assignees, also by decade and country. The results are slightly different, as some patent applications mention several assignees. On this basis, five major periods can be identified, their specificities resulting from technological change, transformation of political environment, and limits of the data.

First, the 1960s appears as a decade slow growth. Although the number of patents nearly tripled, going from 438 in 1960 to 1,103 in 1969, the overall level was still low in comparison to the following decades. This period was dominated by X-ray equipment and mechanical instruments; it did not see major technological transformation except for the development of pacemakers. The United States occupied a dominant position during the decade, with 30.4% of assignees, while Germany was second with 13.8%. Companies from both countries had a strong competitive advantage in the core technologies for medical equipment. Moreover, one must note the quasi-absence of Japanese patents, despite companies in the country being innovative and carrying out research during the 1960s. The bias relates to the fact that Japan only adopted IPC in 1978 and did not apply IPC codes to numerous



Source: PATSTAT

Figure 1: Patent applications for medtech, 1960-2014



Source: PATSTAT

Figure 2: Cumulative evolution of patent application in medtech for major countries, 1960-2014

Table 1: Assignees of medtech patent applications by country and decade, 1960-2014

	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2014	TOTAL
Total World	5577	23282	65758	95974	247229	209579	647399
USA	1698	5064	8825	22120	75821	50933	164461
%	30.4	21.8	13.4	23.0	30.7	24.3	25.4
Germany	772	2025	3611	7902	16253	9202	39765
%	13.8	8.7	5.5	8.2	6.6	4.4	6.1
Japan	107	4572	24707	33227	58055	33484	154152
%	1.9	19.6	37.6	34.6	23.5	16.0	23.8
Switzerland	115	305	378	854	3261	1746	6659
%	2.1	1.3	0.6	0.9	1.3	0.8	1.0
China	0	0	763	4706	24349	39057	68875
%	0.0	0.0	1.2	4.9	9.8	18.6	10.6
USSR/Russia	138	4166	17061	7411	11386	6634	46796
%	2.5	17.9	25.9	7.7	4.6	3.2	7.2
Korea	2	13	131	729	7283	10625	18783
%	0.0	0.1	0.2	0.8	2.9	5.1	2.9
Spain	50	107	155	384	973	885	2554
%	0.9	0.5	0.2	0.4	0.4	0.4	0.4
India	0	4	20	41	40	41	146
%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	848	3349	7131	12736	44474	32040	100578
%	15.2	14.4	10.8	13.3	18.0	15.3	15.5
Unknown	1847	3677	2976	5864	5050	24502	43916
%	33.1	15.8	4.5	6.1	2.0	11.7	6.8
Difference	0	0	0	0	284	430	714
%	0.0	0.0	0.0	0.0	0.1	0.2	0.1

Source: PATSTAT

former patents, particularly during the 1960s (Kawashima & Shimizu 1989).

Second, a first period of high growth is evident during the next two decades, with the number of patent applications peaking at 8,814 in 1989. The most important technological change during the 1970s and 1980s was the advent of electronics, a paradigm shift in the medtech industry, because core technology shifted from mechanics and electricity to electronics. The most important equipment from these two decades was undoubtedly computed tomography (CT scanners). Although the technology was developed in the United Kingdom by the company Emi in 1971 (Le Vine 2010), US and German X-ray companies entered the new business field soon thereafter and dominated the market of CT-scanner equipment by the end of the 1970s (Blume 1992). Technological innovation was thus not an opportunity for the emergence of newcomers; rather, it strengthened the position of dominant companies (Gelijns & Rosenberg 1999). Moreover, one can observe a change of balance between the United States and Germany on the one side (relative declines to 13.4% and 5.5% in the 1980s, respectively) and the fast growth of Japan, which accounted for 37.7% of assignees in the 1980s. The rise of Japan as a leader was not the only effect of the country's adoption of the IPC—the competitiveness of Japanese electronics companies was another. One question to keep in mind, however, is if these assignees were from large diversified giant companies or specialized medtech firms (see the next section).

Third, the 1990s was a decade of stagnation and decline, with an average of 8,586 applications per year and a low of 7,875 in 1995. The major explanation for this stagnation was the collapse of the USSR, which was actively engaged in R&D in the medtech industry and even had a share of assignees of 25.7% in the 1980s—higher than the United States and second after Japan. The Russian share in the 1990s, however, dropped to 7.7%. At the exception of the Soviet case, then, one can see a continuing growth of patent applications by major countries, led by Japan in front of the United States and Germany. China also appeared during the decade, with 4.9% of assignees in the 1990s against 1.2% in the 1980s. Still, the absence of a major breakthrough innovation during the decade contributed to the sluggish growth of patent applications.

Fourth, the medtech industry experienced a new period of high growth between 1998 and 2009, with the patent application total going from 9,616 to 22,566. A new technological change supported a renewal of R&D and the entry of numerous newcomers: information and communication technology (ICT). Knowledge developed outside the field of traditional medtech began to find applications in medical equipment and devices, such as items for diagnosis or assisted surgery. On this point, too, it will be necessary to examine whether the technological change was an opportunity for newcomers to enter the medtech industry or not. Regarding the location of assignees, a shift between the United States (30.7% from 2000 to 2009) and Japan (23.5%) was again realized. Both countries, however, accounted for more than half of all assignees. China established itself as number three (9.8%) before Germany (6.6%).

Finally, a fifth period—one of accelerated growth—has taken shape since 2009. The number of patent applications reached 36,613 in 2014, or 61% more than the number in 2009. The driver of this fast growth has not been a major technological innovation, but rather the rise of Chinese assignees.

From 2010 to 2014, China became the second-leading company with 18.6% of the world's assignees, topping Japan (16%) and getting closer to the United States (24.3%). A look at the largest Chinese assignees during this period shows the domination of universities and public research organizations. Six of the top ten appliers were universities, including the first (Chinese Academy of Sciences, 849 applications) and the second (Shanghai Jiao Tong University, 360 applications). Interestingly, the four companies include neither any state-owned enterprise nor any firm with foreign capital. The first joint venture with a Western firm was Siemens Shanghai Medical Equipment (11,220 applications). Section 5 examines the basic data about Chinese largest assignees in regard to Western and Japanese cases.

Table 2: Assignees of medtech patent applications by category, 1960-2014

	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2014
Assignees total						
USA	1698	5062	8825	22120	75661	50703
Japan	115	4572	24707	33220	58050	33470
Germany	772	2025	3610	7891	16250	9202
Switzerland	115	305	378	854	3261	1744
Firms, as a %						
USA	67.6	57	51.7	59.8	37.1	33.3
Japan	86.1	85.4	92.8	92.6	78	74.2
Germany	72.9	72.4	59.4	53.8	57.9	62.2
Switzerland	67	67.2	76.5	76.1	70.2	62.8
Firms, average						
USA	3.38	3.35	3.03	4.05	5.6	4.94
Japan	3.3	8.47	23	19.5	23	24.65
Germany	6.12	8.83	7.01	6.14	9.21	8.74
Switzerland	2.57	3.36	3.01	4.19	8.27	5.86
Top 10 firms, patents						
USA	289	658	1049	3031	10112	6202
Japan	75	2331	15660	18808	28456	17963
Germany	394	972	1337	2259	5970	3651
Switzerland	53	129	138	355	1466	680
Top 10 firms, % of total firms						
USA	25.2	22.8	23	22.9	36	36.8
Japan	75.8	59.7	68.3	61.1	62.9	53.7
Germany	70	66.3	62.3	53.2	63.4	63.8
Switzerland	68.8	62.9	47.8	54.6	64	62.1
Individuals, as a %						
USA	25.9	36.3	40.5	33.4	58.1	61
Japan	13.9	14.3	6.9	6.7	17.6	20.7
Germany	23.7	27.3	37	43.9	38.8	33.5
Switzerland	33	32.5	23.5	23.2	27.1	32.4
Individuals, average						
USA	1.37	1.24	1.21	1.29	1.59	1.62

Japan	1.23	1.4	1.68	1.42	1.75	1.94
Germany	1.38	1.35	1.38	1.36	1.58	1.49
Switzerland	1.12	1.3	1.33	1.29	1.43	1.42
Universities and R&D centers, as a %						
USA	6.5	6.7	7.8	6.8	4.8	5.7
Japan	0	0.3	0.3	0.7	4.4	5.1
Germany	3.4	0.3	3.6	2.3	3.3	4.2
Switzerland	0	0.3	0	0.7	2.6	4.8
Universities and R&D centers, average						
USA	5.33	4.24	4.57	6.05	14.6	11.6
Japan	0	1.43	1.06	2.16	9.06	7.32
Germany	3.71	1.4	4.06	4.07	4.39	4.53
Switzerland	0	1	0	1.2	4.1	7

Source: PATSTAT
Note: the number of patents for the last column is based only on a five-year period, against ten-year for the others. This difference impacts on the average number of patents.

Table 2 shows the results of the breakdown of assignees into three categories (enterprises, individuals, and universities and research centers, with the third category including government agencies in the case of the United States), highlighting a different evolution between the four countries. The following section details the dynamics.

Firms are the most important assignees, regardless of country or period, except for the United States and Japan since 2000, when individuals became the largest assignees. A look at the largest individual assignees in the United States and Japan after 2000 also shows that most have been engineers in large corporations (see section 5). The reason why these companies increased the use of their engineers' names as (co-) assignees is unclear. It is not related to a change in regulation regarding patenting in the United States (the Leahy-Smith America Invents Act was modified in 2012) but obviously to a new practice by firms, probably in-firm rewards for innovative employees. Despite this bias, the domination of firms is remarkable; however, the trend is different between the United States and Germany, where the share of companies declined between the 1960s and the 1990s, and Japan and Switzerland, where firms exhibited a growing presence during the period in question. A look at the positions of the most important companies in the medtech industry shows additional differences. The share of the top 10 largest firms sits at a lower level in the United States but presents an increasing concentration in the country. In Japan, Germany, and Switzerland, the position of the top 10 largest firms decreased until the 1990s and then increased again thereafter. Since 2000, then, the concentration of R&D has been a global trend. The next section discusses the changes expressing the dynamics at that time in Japan, Germany, and Switzerland. However, beyond these variations, firms in all the countries share a similarity: a growing average number of patents, which means that firms built organizational facilities for R&D and invested more in this activity.

Individual assignees are the second-largest actor in patent applications in the global medtech industry. They have a particular significant weight in the United States for the reasons explained above. From a perspective encompassing the four countries, including the United States, though, the average number of applications per assignee remains low—constantly below two—although a slight increase is noticeable.

Finally, universities and R&D centers present a different evolutionary picture. They carved out a strong position in the United States in the 1960s, followed by Germany in the 1980s, but the growth of their presence is a relatively new phenomenon in Japan and Switzerland. The expansion started after 2000 in these two countries, which have both surpassed Germany. Moreover, the domination of US universities is evident in the high number of average patent applications per institution.

5. Varieties of models

This section tackles the four national cases. We focused on the largest assignees and carried out a qualitative analysis to discuss the evolution of competitive advantages of various actors more clearly. We selected the 20 leading firms, 10 leading individuals, and 10 leading universities (with at least 3 applications) for each decade and produced a database. The objective is to present various models of innovation in the medtech industry.

The United States: The birth of medtech big business

Patent applications in the United States capture the birth and growth of medtech big business: the emergence and domination of large enterprises specializing in medical technology. Data on the top 20 firms reveals three main characteristics. First, the companies are large research organizations. They apply for a large and growing number of patents over time, like Japanese firms but unlike German and Swiss companies. Second, there are very few foreign companies in the mix. One of the few is among the world's largest electrical appliances companies with a healthcare device division (Siemens appeared in the top 20 during the 1990s), while the British company Smith & Nephew specializes in orthopedic devices and implants (and appeared in the top 20 during the 1990s and 2000s). A final exception is Covidien, the former medtech division of Tyco Healthcare legally based in Ireland but managed from the United States, putting it in the "US company" category. Third, one can observe a strong tendency toward specialized medtech firms (from 52.2% of the top 20 firms in the 1960s to 82.2% since 2000), which constitute a much larger proportion than in other countries. In the 1960s, there were still numerous companies from other sectors of the manufacturing industry that had a medtech divisions, like firms in general electric appliances (General Electric, Westinghouse), electronics (Hewlett-Packard, IBM), pharmaceuticals (Baxter Laboratories, Park, David & Co.), and diversified conglomerates (3M, American Cyanamid, Barnes Engineering). This type of company setup disappeared during the following decades, however, while specialized firms like Boston Scientific, Depuy, Ethicon, or Medtronic became the largest innovators in the US medtech industry. In many cases, this shift occurred through specialized firms executing takeovers of medtech organizations at former diversified companies. Boston Scientific is a case in point. The firm launched in 1979 went public in 1992, later engaging in the takeover of several companies and divisions (Rodengen 2001). M&A has probably been the main vector of growth among US medtech firms since the 1990s. The sources for this article, however, do not enable us to discuss this issue further. Moreover, giant US medtech companies have expanded internationally since the 1990s. After 2000, Stryker was in the top 20 of firm innovators in Germany and Switzerland, while six other US medtech companies placed in the Swiss ranking.

As for individual assignees in the United States, the large average amount of patents applied for is a salient point, a number much higher than those of other countries investigated here. The most important trend is the growing prominence of medical doctors until the 1990s, followed by a decline and the emergence of engineers as key innovators. University professors have had a minimal presence, but that does not mean that universities are not important places of innovation. Indeed, many of the medical doctors are people working at hospitals, like Michel Mirowski, a doctor born in Poland who migrated to Israel and then to the United States, where he carried out research on the pacemaker. Though a medical doctor, he worked at Johns Hopkins University and applied for a total of 12 patents during the 1980s. Entrepreneur surgeons are also worth mentioning, as they were quite numerous in the United States relative to other countries. Peter J. Wilk, a surgeon in New York City and manager of an IP business (Wild Patent Management Corporation), applied individually for 79 patents during the 1990s. One remaining point of discussion is the way these medical entrepreneurs cooperated with medtech firms. Finally, engineers (including technicians and mechanics) show a constant decline followed by a rebirth in the 1990s. There was, however, a major change, as the first generation of engineers were mostly owners of small enterprises themselves, while their counterparts since the 1990s have tended to work for large corporations.

Table 3: Largest innovators in the US medtech industry, 1960-2014

	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2014
Top 20 firms (min. 3 patents)						
N	23	20	20	20	20	20
Patent total	478	931	1417	3901	12319	7657
Patent average	20.8	46.6	70.9	195.1	616.0	382.9
US firms	23	20	20	18	17	17
as a %	100.0	100.0	100.0	90.0	85.0	85.0
US medical firms	12	15	14	14	15	15
as a % of US firms	52.2	75.0	70.0	77.8	88.2	88.2
Top 10 individuals (min. 3 patents)						
N	11	16	10	10	11	10
Patent total	62	128	111	281	379	450
Patent average	5.6	8.0	11.1	28.1	34.5	45.0
Medical doctor	3	5	3	6	0	-
as a %	27.3	31.3	30.0	60.0	0.0	-
University professor	0	2	3	2	1	-
as a %	0.0	12.5	30.0	20.0	9.1	-
Engineer	6	6	3	1	9	-
as a %	54.5	37.5	30.0	10.0	81.8	-

Unknown	2	3	1	1	1	-
as a %	18.2	18.8	10.0	10.0	9.1	-

Source: PATSTAT
Note: the 10 largest individual patent assignees in 2010-2014 had all a Chinese name. It was impossible to identify them due to a high number of individuals with the same patronym.

Japan: The lasting competitive advantage of electronics multinationals

The Japanese medtech industry is characterized by its stability over time. With companies long the dominant force in the country, no major changes regarding these actors have occurred. The quasi-absence of foreign companies is a striking feature and makes Japan a unique case. The only company with foreign capital to appear in the top 20 ranking since the 1960s is GE Yokogawa Medical System, a joint venture founded in 1982 by GE and Yokogawa Electric, specializing in X-ray and MRI equipment. It ranked as the fifth-largest patent applicant in the 1990s but disappeared from the list after 2000. Olympus and Toshiba have occupied the top two spots since the 1960s—without any exception. Finally, 12 of the 20 largest firms from 2010 to 2014 were already in the 1970s ranking.

This long-term stability is an illuminating window on the management of innovation by large Japanese firms in high-tech industries. Looking at laser components, Shimizu (2016) demonstrated that Japanese companies reallocate resources internally to shift toward R&D in new technology, while US entrepreneurs take technological change as an opportunity to create new firms. The Japanese employment system and career path for engineers make it difficult and highly risky to quit a company for founding a startup, however, which also explains the low proportion of companies specializing in medical devices; Omron, Shimadzu and Terumo are three of the select few, and there are hardly any newcomers. The overwhelming majority of Japanese medtech companies are large multinational enterprises in the electronics (e.g. Epson, Hitachi, Panasonic, Sony, and Toshiba) or optical instruments (e.g. Canon, Minolta, Nikon, and Olympus) industries. They have the financial resources to keep investing in R&D for new fields, as the growing average of patents indicates, peaking at nearly 1,700 in the 2000s. For the entire period from 1960 to 2014, Toshiba applied for more than 20,000 patents.

In this context, what position do individual innovators occupy? The answer to that question differs according to the specific time period, of which there are two. First, during the 1970s and the 1980s, university professors and researchers working in academics—both in departments of medicine and engineering—were dominant. It is not possible, on the basis of patent applications, to understand the extent to which they cooperated with the large companies that dominated the medtech industry. Some cases suggest joint research between industry and academics. For example, Ken Ishihara, the individual assignee with the second-largest number of patents in the 1990s (30 applications), was a researcher in the Faculty of Medicine at Osaka University and professor of medicine at Ehime University and researched ultrasonic diagnostic apparatuses with engineers from Hitachi. Second, since 2000, nearly all of the largest individual assignees have been engineers at large electronics firms. For the years 2010–2014, all of them were from Fujifilm.

Table 4: Largest innovators in the Japanese medtech industry, 1960-2014

	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2014
Top 20 firms (min. 3 patents)						
N	8	20	20	20	20	20
Patent total	71	2723	18177	22458	33924	20258
Patent average	8.9	136.2	908.9	1122.9	1696.2	1012.9
Japanese firms	8	20	20	19	20	20
as a %	100.0	100.0	100.0	95.0	100.0	100.0
Japanese medical firms	0	2	5	7	6	5
as a % of Japanese firms	0.0	10.0	25.0	36.8	30.0	25.0
Top 10 individuals (min. 3 patents)						
N	0	8	10	17	10	10
Patent total	0	70	184	181	226	514
Patent average	-	8.8	18.4	10.6	22.6	51.4
Medical doctor	-	4	0	2	0	0
as a %	-	50.0	0.0	11.8	0.0	0.0
University professor	-	0	6	12	1	0
as a %	-	0.0	60.0	70.6	10.0	0.0
Engineer	-	2	3	1	8	10
as a %	-	25.0	30.0	5.9	80.0	100.0
Unknown	-	2	1	2	1	0
as a %	-	25.0	10.0	11.8	10.0	0.0

Source: PATSTAT

Germany: The coexistence of Siemens and specialized medtech SMEs

The main characteristic of the German medtech industry is the overwhelming domination of Siemens. Since the 1960s, it has permanently occupied the first rank of the largest innovators and has even strengthened its dominance over time. On the whole, from 1960 to 2014, Siemens has applied for a total of 7,473 patents—18.8% of all patents applied for by Germany-based organizations and individuals over the period in question. Through its American subsidiary, Siemens has also lodged itself in the top 20 largest medtech innovators based in the United States. Siemens's success relies on a historical competitiveness in the field of medical imaging and a diversification into healthcare IT management since the 1990s (Brooks & Grotz 2010). Beside Siemens, the largest innovative companies in Germany exhibit two main features. First is the presence of foreign enterprises, which became important in the 1990s. The proportion of foreign companies is higher than those in the United States and Japan but lower than the ratio in Switzerland. The corresponding firms are among the largest medtech companies of the world, like Philips (the Netherlands), Olympus (Japan), and Stryker (USA), as well as subsidiaries of pharmaceutical giants like Roche (Switzerland) and Sanofi (France). Most of them entered the German medtech industry through over the takeover of a domestic company. Second, as has been the case in the United States, German firms have shown a growing specialization in medical technology over time. Moreover, the companies have demonstrated long-term sustainability. A large number of German medtech companies for the years 2000–2014 were already in the top 20 in the 1970s (Aesculap, Draegerwerke, Erbe Elektromedizin, Karl Storz, and Richard Wolf). Almost all of them date back to the nineteenth century, except the last two, which were founded in 1945 and 1947, respectively.

As for individual innovators, the top-10 ranking shows a persistent presence of engineers (including technicians and mechanists) in the upper echelon. Among them are many entrepreneurs, like Lutz Biedermann (1990s), Erich Jaeger (1960s-1970s), Thomas Koehler (2000s), Norbert Lemke (1990s), Harald Maslanka (1980s), Peter Osypka (2010s), Rudolf Rodenstock (1960s), Blasius Speidel (1970s) and Dieter von Zeppelin (1970s–1980s). A shift toward engineers working at large corporations is evident after 2000, but the trend is less marked than it is in other countries. Medical doctors and university professors, meanwhile, have cooperated with small medtech companies; joint patent applications often point to this approach. One example is the case of Juergen Harms, a professor of orthopedics at Saarland University, who co-developed medical devices with Biedermann Motech in the 1990s.

Table 5: Largest innovators in the German medtech industry, 1960-2014

	1960-1969	**1970-1979**	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2014**
Top 20 firms (min. 3 patents)						
N	21	22	21	20	20	21
Patent total	467	1148	1552	2554	6626	4182
Patent average	22.2	52.2	73.9	127.7	331.3	199.1
German firms	20	21	19	17	15	14
as a %	95.2	95.5	90.5	85.0	75.0	66.7
German medical firms	13	11	12	13	10	11
as a % of German firms	65.0	52.4	63.2	76.5	66.7	78.6
Top 10 individuals (min. 3 patents)						
N	5	13	13	10	16	11
Patent total	30	94	123	142	281	121
Patent average	6.0	7.2	9.5	14.2	17.6	11.0
Medical doctor	2	3	2	3	1	1
as a %	40.0	23.1	15.4	30.0	6.3	9.1
University professor	0	1	3	3	1	0
as a %	0.0	7.7	23.1	30.0	6.3	0.0
Engineer	3	7	5	4	13	10
as a %	60.0	53.8	38.5	40.0	81.3	90.9
Unknown	0	2	3	0	1	0
as a %	0.0	15.4	23.1	0.0	6.3	0.0

Source: PATSTAT

Switzerland: The globalization of a medtech cluster

General data demonstrated that the Swiss medtech industry was characterized by a growing number of firms—with a declining concentration of R&D at the largest firms—between the 1960s and the 1990s, after which the trend reversed course (fewer firms but more concentration). A qualitative analysis of the top 20 firms uncovers two major features.

First, the growing importance of firms until the 1990s resulted from the development of companies specializing in medtech (50% of Swiss firms in the 1960s and 1970s; 80% in the 1990s). While the ranking of Swiss firms in the 1970s included companies from other manufacturing industries (Biviator; from watches and measuring instruments; Brown, Boveri & Co.; from electrical equipment; Contraves, from armaments), financial services (Atlantis and Rhône Consult), and the pharmaceutical industry (Roche and Sandoz), most of them disappeared from the ranking in the 1990s, save for a watch company (Asulab) and two pharmaceutical giants (Ciba-Geigy and Roche). Medtech business then shifted from a secondary activity, developed through diversification, toward a core business. Since 2000, the rate of specialization has declined due to the entry of new actors attracted by the growth of healthcare business (Nestlé and CSEM, a small company specializing in R&D) and the permanence of pharmaceutical firms (i.e. non-specialized medtech firms). Moreover, a distinctive feature of the Swiss firms is a strong specialization in two fields: orthopedics and diagnostic systems, the latter of which are a major development focus for pharmaceutical companies.

Second, the early and fast-growing globalization of the Swiss medtech industry is remarkable. While there were only Swiss firms in the 1960s, the first company with foreign capital appeared in the 1970s (Storz Endoskop, from Germany). The percentage of foreign firms reached 28.6% in the 1990s and more than 50% in 2010–2014. During the latter period, these firms were from the United States (7), Germany (3), and Sweden (1). Although a few entered the industry through mergers with Swiss firms (Cilag International and Medos International merged by Johnson & Johnson; Centerpulse taken over by Zimmer), most resulted from greenfield investment. Global companies thus founded subsidiaries in Switzerland to benefit from localized knowledge, particularly in the field of orthopedics, thereby using Switzerland as a part of their R&D strategies. Consequently, the twofold trend toward specialization and globalization led to significant renewal of firms. In the years from 2010 to 2014, only 14.3% of firms in the ranking had been in the top 20 in the 1970s.

As for the evolution of the most prominent individual innovators, it is hard to make any relevant analysis until the 1980s due to their small numbers. Since the 1990s, the growing importance of engineers is striking. A major factor behind this change has been the development of departments and degrees in bioengineering at the Federal Institutes of Technology of Lausanne and Zurich. The career paths of these engineers indeed show that the graduates tend not to go on to become technical heads of R&D departments at large multinationals, like US and Japanese top innovators often do, but rather engage in a flexible medtech cluster focused on orthopedics. Belonging to a common community, they move between universities, startups, and larger enterprises. For example, Robert Frigg, the leading individual innovator between 1990 and 2014 (27 applications), started his career as a mechanist in 1978 at the research institute AO, specializing in orthopedics, and then worked during the 1980s as a project director at AO and the University of Bern. He was appointed chief technology officer at Synthes (2004) and served as a consultant, coach, and board member at several startups. He eventually became honorary professor in the Faculty of Medicine at the University of Zurich in 2008.[1] Human capital, as this example illustrates, is a major reason explaining the entry of foreign firms into the Swiss medtech industry.

Table 6: Largest innovators in the Swiss medtech industry, 1960-2014

	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2014
Top 20 firms (min. 3 patents)						
N	8	15	21	21	22	21
Patent total	49	146	194	430	1673	781
Patent average	6.1	9.7	9.2	20.5	76.0	37.2
Swiss firms	8	14	17	15	13	10
as a %	100.0	93.3	81.0	71.4	59.1	47.6
Swiss medical firms	4	7	8	12	9	6
as a % of Swiss firms	50.0	50.0	47.1	80	69.2	60.0
Top 10 individuals (min. 3 patents)						
N	1	5	3	10	13	13
Patent total	3	20	12	38	91	81
Patent average	3	4	4	3.8	7	6.2
Medical doctor	0	0	2	3	0	0
as a %	0.0	0.0	66.7	30.0	0.0	0.0
University professor	0	0	0	1	0	0
as a %	0.0	0.0	0.0	10.0	0.0	0.0
Engineer	0	1	0	2	10	12
as a %	0.0	20.0	0.0	20.0	76.9	92.3
Unknown	1	4	1	2	2	1
as a %	100.0	80.0	33.3	20.0	15.4	7.7

Source: PATSTAT

6. Discussion and conclusion

The statistical analysis of patent applications in the global medtech industry between 1960 and 2014 enabled us to emphasize general growth over the long run with two major periods of acceleration that correspond to the incorporation of new technology in the industry (electronics in the 1970s and 1980s and ICT since 2000). These two periods also correspond to the relative dominance of two nations: Japan and the United States, respectively.

Moreover, the focus on four major countries in the medtech industry (the United States, Japan, Germany, and Switzerland) highlighted a variety of models regarding the main industry actors. In the United States, General Electric, along with large and new medtech companies, dominate; Germany is characterized by the growing supremacy of Siemens and the persistence of traditional medium-sized medtech firms; Japan has seen general electronics firms maintain constant leadership; and the largest

[1] https://www.uzh.ch/de/about/portrait/awards/hc/2008/med2.html and https://www.linkedin.com/in/robert-frigg-7070088b/ (accessed June 30, 2019).

innovators in Switzerland are a growing number of foreign companies and a few traditional medium-sized medtech firms.

Some of the factors behind these differences are the consequences of different national innovation systems (Freeman 1995) or the expressions of different varieties of capitalism (Hall & Soskice 2001). In Japan, for example, large companies carry out R&D internally; innovation is more market-based in the United States, with a large number of startups that can grow through IPO or mergers with other companies (Shimizu 2016). Such approaches do not fully explain the peculiarities of national models in the medtech industry, however. The perspective of industry studies argues that the dynamics of any industry should be analyzed and understood on the basis of its specificities (Bouwens, Donzé & Kurosawa 2017). The medtech industry has a history of domination by multinational enterprises in the electrical appliance industry, such as General Electric, Philips, Siemens, and Toshiba (Donzé & Wubs 2019). These firms acquired knowledge for the development of X-ray devices in the interwar years and pursued their investments, sometimes through M&A, to maintain their competitive advantage in the medtech industry through the present day (Gelijns & Rosenberg 1999). Therefore, countries with the presence of such firms—the United States, Germany, and Japan, for instance—are identifiable as dominant players through their patent application data. Another specificity of the medtech industry is the presence of numerous small companies, sometimes clustered in cities or regions that co-develop devices with and for medical doctors (Donzé 2016). Such clusters developed in Germany and Switzerland, in particular, and explain the presence of long-lasting small companies and individual entrepreneurs in the rankings of leading innovators. In the case of Switzerland, this factor contributed to attracting numerous foreign firms, as a large number of non-Swiss companies entered the local medtech industry through mergers with local companies.

Consequently, this empirical analysis of patent applications in the global medtech industry contributed to a better understanding of the industry dynamics on three main points. First, it demonstrated the lasting competitive advantage of large multinationals in the electrical appliance industry. In this sense, it confirmed a major part of the literature on the medtech industry. However, the positions of these various companies differ between countries. While General Electric and Siemens are not only dominant innovators in their home countries but also abroad, respectively Japan and the United States, Toshiba focused its R&D on Japan. Second, the analysis showed the emergence, particularly in the US, of large, specialized medtech companies, such as Medtronic and Stryker. The development of these firms has not been a specific research focus in the existing literature. Most of the companies in this category emerged from clusters of SMEs and startups and achieved dramatic growth that led to the establishment of a new model for medtech multinationals. Third, traditional SMEs maintained their competitive advantage in Germany and, to some extent, Switzerland, as well. Traditional SMEs are minority actors in the United States and Japan, however, where large firms dominate. Discussions of innovation in medtech clusters should thus address this different segment. Fourth, and finally, our study has emphasized a general trend toward the domination of firms specializing in the medtech industry. Whoever the dominant actors may be, companies from the general manufacturing industry have basically vanished from the medtech sphere since the 1970s—an obvious consequence of the high technological barriers to entry into the medtech business.

Based on these findings, further research will focus on two areas that we could not analyze through patent applications. The first is the role of mergers and acquisitions (M&A) in the processes of growth and internationalization. It is necessary to understand how multinationals, large medtech firms, and specialized SMEs have internalized the knowledge that enabled them to grow and expand in the global market. A second major issue is the role of universities. As patents are applied for individually by professors and researchers in most cases, the sources for this paper could not shed light on how universities cooperated with private companies or how academic research has nurtured the development of medtech companies around the world.

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