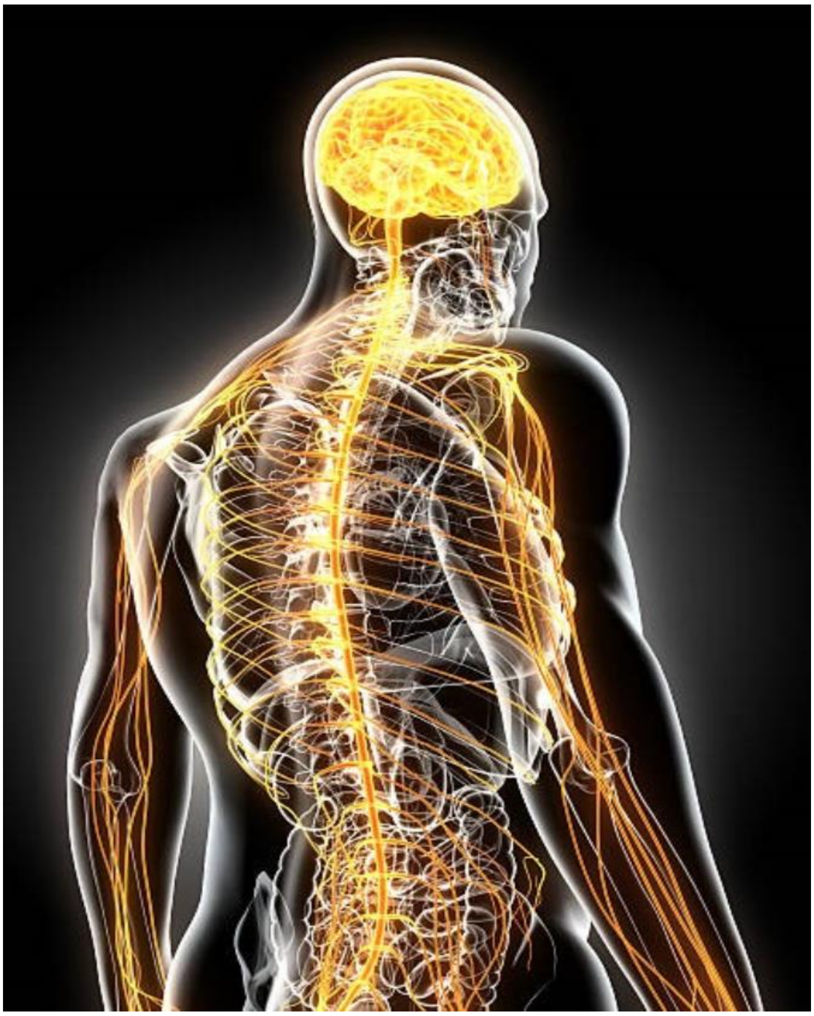

Innovation in Neurosurgery: a market analysis

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Summary

1. Introduction

Neurosurgery is a highly specialized medical field that treats pain and pathological processes that affect the function and or activity of the central nervous system (i.e., brain, hypophysis, and spinal cord), the peripheral nervous system (i.e., cranial, spinal, and peripheral nerves), the autonomic nervous system, the supporting structures of these systems (i.e., meninges, skull and skull base, and vertebral column), and their vascular supply (i.e., intracranial, extracranial, and spinal vasculature). Although neurosurgery is primarily a surgical specialty, activities include both non-operative (i.e., prevention, neurology, trauma care, radiology, diagnosis – including image interpretation – and treatments such as, but not limited to neuro-critical intensive care and rehabilitation) and operative (i.e., endovascular surgery, functional and restorative surgery, stereotactic radiosurgery, and spinal fusion – including its instrumentation) management. There are around 600 different forms of neurological conditions, which are essentially classified into conditions with sudden onset (i.e., acquired brain injury or spinal cord injury), conditions that are intermittent and unpredictable (i.e., epilepsy, cluster headache, or the early stages of multiple sclerosis), conditions that worsen with time (i.e., motor neuron disease, Parkinson's disease, or the later stages of multiple sclerosis), and neurological disorders that are stable (i.e., post-polio syndrome, or cerebral palsy in adults) [4]. Consequently, neurosurgeons specialize in various subfields of the discipline, such as spine surgery, neuro-oncology, pediatric neurosurgery, neuro-intensive care functional neurosurgery and more.

According to a report by MarketsandMarkets (2021)[1], the global neurosurgery devices market is expected to grow from $7.3 billion in 2020 to $13.5 billion by 2026. The report attributes this growth to several factors, including the increasing prevalence of neurological disorders, the growing demand for minimally invasive surgeries, and the development of advanced neurosurgery technologies. In this sense, advanced imaging technologies, such as magnetic resonance imaging (MRI) and computed tomography (CT), have enabled neurosurgeons to visualize the brain and nervous system better, making planning and performing minimally invasive procedures easier. As the demand for minimally invasive surgeries continues to grow, we expect to see continued innovation in the neurosurgery technology market, leading to improved outcomes for patients with neurological disorders. In this setting, developing new and innovative robotic technologies will be critical for meeting the needs of

[1] MarketsandMarkets. (2021). Neurosurgery devices market by product, application, end user - global forecast to 2026. Retrieved from https://www.marketsandmarkets.com/Market-Reports/neurosurgery-devices-market-133872082.html

patients and healthcare providers, making robotic-assisted surgery (RAS) a relatively new area in neurosurgery whose full market potential has yet to be achieved.

As a result of these factors, the neurosurgery technology market and especially neurosurgical robotics are an under-researched field with great potential for both primary and applied science and for developing novel technologies that can address current health challenges in society. The present market analysis aims to explore and understand the neurosurgery technology market, focusing on neurosurgical robotics. Studying this market in its earliest stages is essential to identify critical industrial players - big companies, SMEs, and startups - and key innovation stakeholders, such as entrepreneurs, incubators and accelerators. In addition, an exhaustive analysis of the landscape of neurosurgery devices and neurosurgical robotics is paramount and will lead to identifying the main trends and drivers in these subareas and discussing their instrumentation.

The goal of this market research is to produce a map for neurosurgery and neurosurgical robotics from different perspectives (i.e., instrumentation, market, industry, governmental regulators, academia, professional communities, civil societies, innovation hubs) so that companies can be aware of these factors before entering the field or expanding into.

Consequently, the present market analysis will address the following objectives:

1. Identifying the top ten stakeholders in the neurosurgery devices field and its main subareas.
2. Deliver detailed knowledge on each subarea's primary market growth factors (drivers, restraints, growth opportunities, and challenges).
3. Examine the industry, academia, governmental medical device regulators, civil societies and professional communities through an analysis of its environment and study the subareas instrumentation and final form remarks on the market of each of them.
4. Forecast the market size in North America, Europe, Asia Pacific (APAC), and the Rest of the World (RoW) in neurosurgery and each of its subareas.
5. Conduct a strategic market analysis, profile key market participants and their core strengths, and monitor and analyze competitive trends in the neurosurgical devices' marketplace, such as expansions, acquisitions, partnerships, and collaborations.

This report will thus assist companies in determining possible ways to better position their company to remain competitive and serve their consumers. It will also help them match their products and services to the relevant identified companies.

2. Neurosurgery Innovation System

Neurosurgery is the only viable solution for various conditions, such as certain patients with aneurysms, epilepsy, abscesses, nerve damage, Parkinson's disease, skull fracture, stroke, and brain tumors. Although not all these disorders necessitate brain surgery, many may benefit from treatment, especially if they offer a risk for more severe health concerns. A brain aneurysm, for example, does not necessitate open brain surgery, but it may be necessary if the aneurysm ruptures. The most common type of brain surgery is craniotomy. On the other hand, the most common cause of brain surgery is the presence of brain tumors. According to MedTech Europe, the market share of medical devices, including medical robotics is shown below according to region.

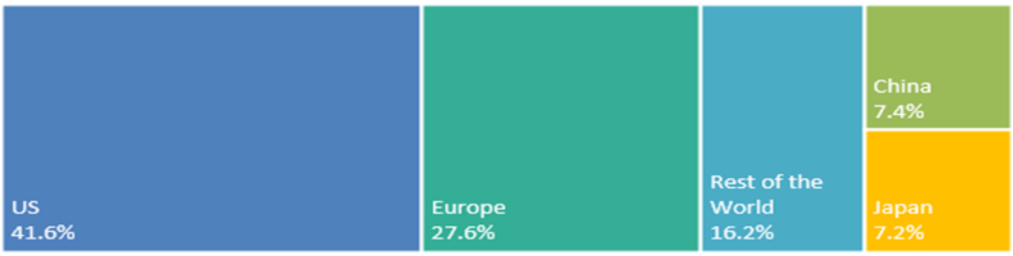

Figure 1. World medical device market by region – 2020 [6]

Similarities are observed between the numbers in Figure 1 and those in Figure 2 concerning the neurosurgery devices market for 2024. However, the rest of the world is gaining interest in other medical devices rather than neurosurgery-oriented devices.

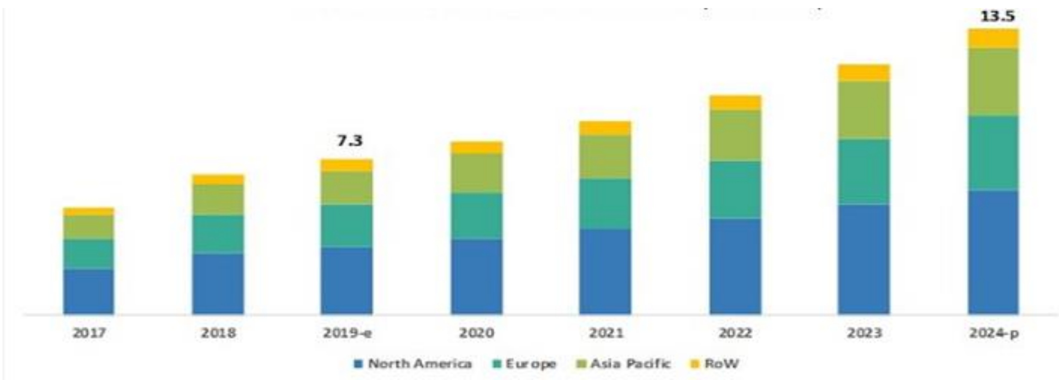

Figure 2. Neurosurgery Devices Market Share in USD Billions from 2017 to 2024, by Region [5]

It is expected to grow at a CAGR of 13%, from USD 7.3 billion in 2019 to USD 13.5 billion by 2024. The increasing prevalence of neurological diseases, efforts to expand the application base for neuromodulation, and the advantages of neuroendoscopic surgeries over traditional brain surgeries propel the neurosurgery devices market forward [5].

Since the referenced analysis was carried out in 2019, a comparison of the market share by region between 2019 and the final year, 2023 was conducted. In 2019, North America dominated the market at 43% followed by the EU at 38.4%, Asia Pacific at 10.5% and the rest of the world at 8%. In 2024, North America will be stable at 43.1%, the EU will decrease to 26.3%, Asia Pacific surprisingly increases to 23.8%, and the rest of the world will decrease to 6.9%. Table 1 presents the big ten global medical device companies that excel in neurosurgery devices, discussed earlier in the introduction with the country of origin, website, description, and their neurosurgery specialty.

Table 1. Big Ten Companies in Neurosurgery

Company	Country	Specialty	Description
Medtronic	The United States	All identified neurosurgery areas	Founded in 1949, Medtronic is divided into four business units: Minimally Invasive Therapies Group, Diabetes Group, Restorative Therapies Group, and Cardiac and Vascular Group. Medtronic designs and manufactures neurosurgery devices and therapies for the area's treatment of over 30 chronic diseases, including heart failure, Parkinson's

Company	Country	Specialty	Description
			disease, Down syndrome, obesity, chronic pain, spinal problems, and diabetes.
B|BRAUN	Germany	Neuroendoscopy	Founded in 1839, B. Braun is a manufacturer of medical devices that specializes in infusion treatment and pain management. B. Braun offers neurosurgeons a one-stop shop for operations on the brain, spine, spinal cord, and peripheral nerves, including goods, procedures, services, and training.
Boston Scientific	The United States	Surgical instruments and invasive neurostimulation	Founded in 1979, Boston Scientific has advanced the practice of minimally invasive medicine by offering a diverse portfolio of products, technologies and services in a variety of medical disciplines. Boston Scientific is continuing to develop in these areas and expanding into new geographies and high-growth

Company	Country	Specialty	Description
			adjacency markets.
nevro	The United States	Invasive Neurostimulation	Founded in 2006, Nevro is a multinational medical device form dedicated to developing breakthrough products that improve the quality of life for those suffering from incapacitating chronic pain. The Senza spinal cord stimulation (SCS) system an evidence-based neuromodulation platform for the treatment of chronic pain, was developed and commercialized by Nevro. The Senza system is the only SCS system that provides Nevro's exclusive HF10 therapy. Nevro's trademarks include Senza, HF10, Nevro, and the Nevro logo.
STORZ KARL STORZ—ENDOSKOPE	Germany	Neuroendoscopy	Karl Storz is a manufacturer of endoscopes for human and veterinary medicine, as well as industrial purposes. The KARL STORZ family company has developed from its humble origins in 1945 to become a global manufacturer

Company	Country	Specialty	Description
			and distributor of endoscopes, medical instruments, and technologies. KARL STORZ's most recent innovations are in digital documentation systems and comprehensive operating room designs. As a system supplier, the business combines its endoscopic knowledge with software solutions to accomplish operating room integration and to enhance clinical process and resource management.
Abbott	The United States	Invasive neurostimulation and surgical instruments	Founded in 1944, Abbott works to control the symptoms of chronic pain and movement disorders such as Parkinson's disease and essential tremor, as well as to decrease the physical and emotional toll. Currently, they have three products lines, spinal column simulation for chronic radiofrequency therapy for chronic pain, and DBS therapy for movement disorders.

Company	Country	Specialty	Description
Ackermann	Germany	Surgical instruments	Founded in 1954, the Ackermann group successfully creates, manufactures and distributes solutions for a wide range of surgical procedures, mainly minimally invasive surgery, but also ligating and spinal implants.
HAWK	Neuroendoscopy	China	Hangzhou HAWK Optical Electronic Instruments Co., Ltd. was established in Hangzhou in 1993. The firm specializes in the design and development of human medical, veterinary and industrial endoscope systems.
adeor MEDICAL	Surgical instruments and neuroendoscopy	Germany	Adeor Medical AG is based on over 40 years of surgical equipment experience. They offer a portfolio of cutting-edge equipment, with an emphasis on applications in neurosurgery, ENT, gynecology and vascular surgery.
MACHIDA	Neuroendoscopy	Japan	Established in 1956, Machida has three business scopes, 1. Medical instrument

Company	Country	Specialty	Description
			manufacturing, import, and distribution 2. Veterinary medical tool manufacturing and distribution 3. Industrial inspection instrument manufacturing, import, and distribution In 2018, it became a subsidiary of Nipro corporation.

Companies play a significant role in the neurosurgery market by contributing to the development, manufacturing and distribution of products and technologies that are essential for the diagnosis and treatment of neurological disorders and conditions. Our research showed that the role of companies in the neurosurgery market includes:

- Research and development: Companies invest heavily in research and development to create innovative neurosurgical devices, instruments and technologies. This includes the development of advanced imaging equipment, surgical tools, implants and software solutions used by neurosurgeons.
- Manufacturing: Companies manufacture a wide range of neurosurgical products, from neuroimaging devices to surgical instruments and implantable devices. High-quality manufacturing is crucial to ensure the safety and efficacy of these products.
- Innovation: Companies drive innovation in the field of neurosurgery by continuously improving existing products and developing new technologies. These innovations often lead to better patient outcomes and more efficient surgical procedures.
- Collaboration: Companies often collaborate with healthcare providers, research institutions and medical societies to advance the field of neurosurgery. These collaborations can lead to the development of new treatment protocols and technologies. We will delve further into the interrelation between the different stakeholders in section 2.2 of this report.

In the neurosurgery market, innovation plays a pivotal role in driving advancements that enhance patient care and surgical practices. Companies operating in this field and displayed in this report are at the forefront of innovation, investing significantly in research and development to create groundbreaking products and technologies. This drives the evolution of neurosurgical technologies, as will be seen in the next part of this report.

2.1. Evolution of neurosurgical technologies

Patents are crucial in the neurosurgery devices market, as in any technology-intensive industry. In the context of neurosurgery devices, patents provide legal protection for innovative ideas, designs, and technologies, allowing companies and inventors to safeguard their intellectual property (IP) and maintain a competitive edge. Patents significantly influence the neurosurgery devices market through a multifaceted impact. They safeguard innovative concepts and cutting-edge technologies, promoting continuous advancement in the field. By granting exclusive rights for a limited period, patents encourage companies and inventors to invest in research and development, resulting in a flow of novel devices and techniques. This exclusivity also empowers patent holders with market dominance, enabling them to control supply and maintain a competitive edge. Patents facilitate licensing agreements, fostering collaboration and generating additional revenue streams. Moreover, they create formidable barriers to market entry, slowing the influx of new competitors and providing incumbents with growth opportunities. In attracting investment, patents signify a robust intellectual property foundation, increasing a company's appeal to stakeholders. Moreover, patents offer legal protection against infringement, allowing patent holders to defend their innovations through litigation if necessary. Ultimately, patents fundamentally shape the neurosurgery devices market by driving innovation, market differentiation, and industry collaboration while balancing exclusivity and advancement. It is important to note that the patent landscape can be complex, and the process of obtaining a patent can vary by jurisdiction. Additionally, not all innovations are patentable—there are criteria that an invention must meet, such as being novel, non-obvious, and useful. As the neurosurgery devices market evolves, patents will remain a fundamental tool for protecting and encouraging innovation in this critical field.
In order to gain a keener understanding of the innovation and scientific landscape in the neurosurgery market, we have conducted a research on patents related to neurosurgery worldwide. By displaying the number of patents in the neurosurgery field over the past ten years (time-length: 2011 - 2021) for the eight leading countries, we can visualize the evolution of innovation and

scientific breakthroughs in the neurosurgery area. Focusing on the top three countries (China, USA and Japan) will show what innovation looks like at the most competitive level.

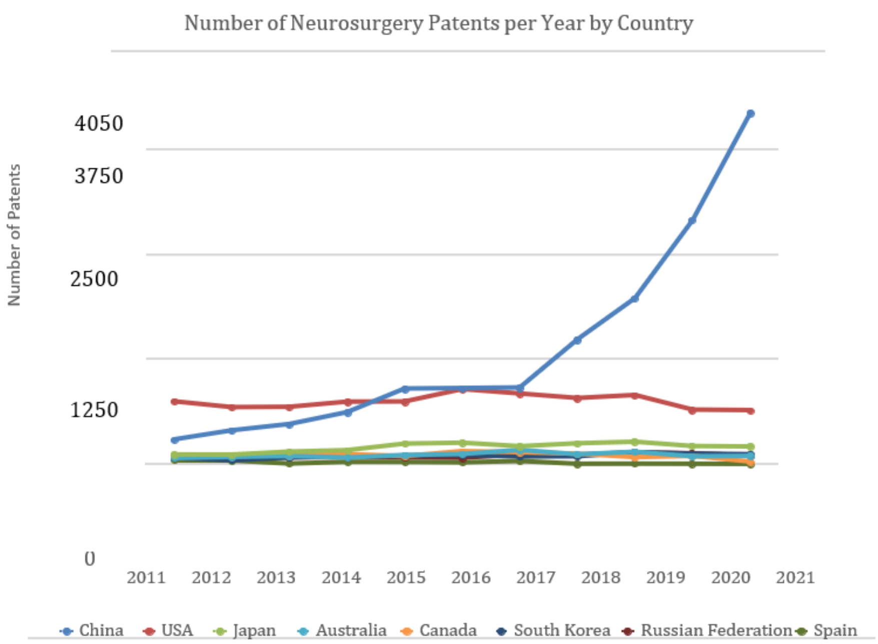

Figure 3. Neurosurgery patents from 2011 to 2020, by Region [5].

The chart showcased in Figure 3 shows a similar innovation progress by patent count among Japan, Australia, Canada, south Korea, the Russian Federation and Spain. China produced on average the highest number of patents in the neurosurgery field. However, from 2018 to 2021 the number of patents was exceedingly larger than previous years, raising some questions as to how these numbers were achieved.

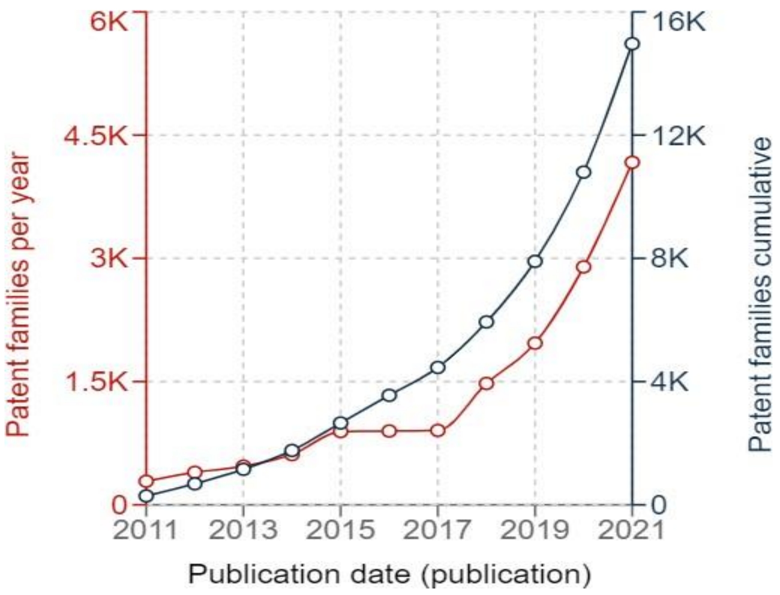

Figure 4. Extract from Espacenet (2022) [7].

As displayed in Figure 4, the largest increase in patent numbers was between 2020 and 2021, increasing from 2899 to 4169 patents. The quick increase in patent filings, including PCT applications, was largely due to a massive surge in patent applications fueled by government subsidies at all levels and fueled by the central government's quantity-first and subsidy-driven instructions to strengthen China's patent level [59].

In the US, the cumulative patent families for neurosurgery appear relatively constant, showing a constant and rational increase in patent numbers yearly, as per Figure 5.

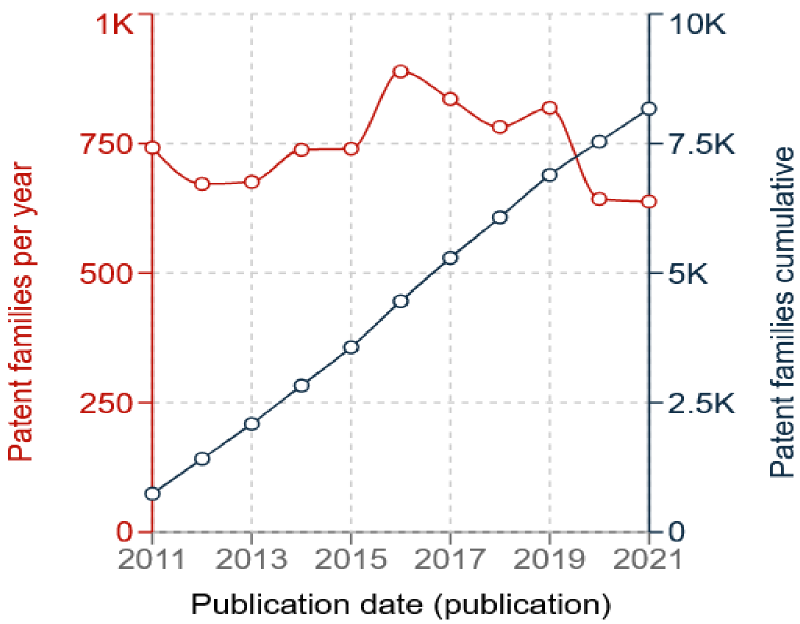

Figure 5. Extract from Espacenet (2022) [7].

Their fastest increase happened from 2015 to 2016, but after that, it was a continuous downhill except for 2019 (see Figure 6). Their most significant reduction in the number of patents produced was in 2020 reducing by 175 patents from 2019 whilst the peak number of patents occurred in 2016. In Japan, the cumulative patent families for neurosurgery appear to be close to a linear function, indicating consistent and sensible growth in patent numbers each year.

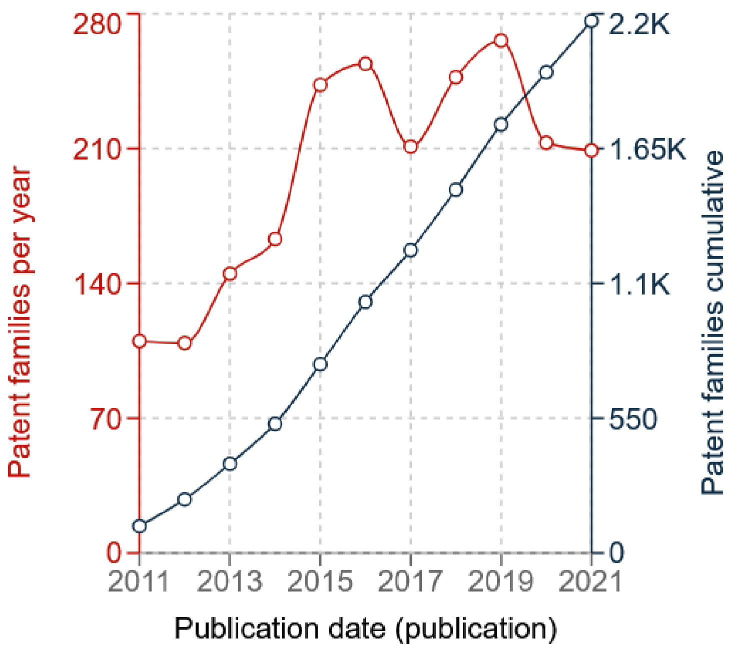

Figure 6. Extract from Espacenet (2022) [7].

The greatest increase in patent numbers can be seen in 2015 increasing by 80 patents from 2014. The steepest drop occurred in 2020 decreasing by 53 patents from 2019. Since 2015, Japan's number of patents has stabilized at a low of 208 patents and a peak of 266. The graph shows that Japan's number of patents seems to behave in a pattern for the last ten years. From the graph, it is observable that since the last ten years, Japan's number of patents seems to behave in a pattern. These numbers go to show that Japan's patents are (of a good quality) reliable and that innovation is on a stable rise. A different approach to measuring innovation is to look at it more broadly, instead of focusing specifically on neurosurgery. This way, we are able to view innovation across the entire domain. The global presence of neurological companies established since 2014 can be found in the Annex in Figure A1 series with an excel sheet of all these companies.

2.2 Analysis of market environment

The analysis conducted in this report is based on a Quadruple Helix analysis. According to the Quadruple Helix Model [45], the four essential actors in the innovation system are academia, policy, industry, and civil society. In order to fit the objectives of this report, the analysis is adjusted to include neurosurgery devices and neurosurgical robotics field. Consequently, the analysis will focus on medical device government regulators instead of general policy in the field. Moreover, we will deepen the civil society stakeholders' analysis by displaying professional communities, adding a valuable twist to the traditional QH analysis. In this sense, an increasing number of governments are encouraging public participation in innovation processes. This report section aims to understand neurosurgical robotics field from a multi-faceted perspective. In this sense, we will elaborate on the four key stakeholders of the neurosurgery landscape. First, at the industry level, we have displayed the field's most prominent professional communities, accelerators and incubators. Said actors bring expertise in manufacturing, marketing, and distribution and access to financial resources essential for scaling up and bringing innovations to the market. At the academic level, we have highlighted the institutions that excel at fundamental and applied research in neurosurgery. These institutions have the expertise to train and develop the next generation of skilled workers and entrepreneurs who can drive innovation forward. This is particularly important in fields such as science and technology where specialized skills and knowledge are required. Thirdly, we review key actors of government policies in the neurosurgical field for different countries. Policymakers are responsible for creating an environment that fosters innovation, promotes sustainable development, and addresses societal challenges. They also play a crucial role in promoting the dissemination and adoption of innovation, as well as ensuring that ethical, legal, and social issues are considered in the innovation process. Finally, we exhibit some *Neuro-health Societies* worldwide. Civil society organizations, such as non-governmental organizations, consumer groups, and community associations, represent the interests of diverse social groups and stakeholders that may be affected by innovation.

2.2.1. Industry

As stated in section 2.1. of this report, patents are crucial in the neurosurgery devices market, as in any technology-intensive industry. In the context of neurosurgery devices, patents provide legal protection for innovative ideas, designs, and technologies, allowing companies and inventors to safeguard their intellectual property (IP) and maintain a competitive edge. Patents significantly influence the neurosurgery devices market through a multifaceted impact. They safeguard innovative concepts and cutting- edge technologies, promoting continuous advancement in the field. By granting exclusive rights for a limited period, patents encourage companies and inventors to invest in research and development, resulting in a flow of novel devices and techniques. This exclusivity also empowers. In the Four Helix Model context, the industry sector assumes a central and transformative role within the neurosurgery devices market. Comprising a dynamic array of companies and entities, this sector drives innovation, economic growth, and improved patient care by conceptualizing, developing, and bringing advanced medical devices explicitly tailored for neurosurgery to market. The industry sector serves as an innovation engine at its core, directing substantial resources toward research and development endeavors.

Industry pioneers (see Table 2) collaborate closely with academic experts and healthcare practitioners to bridge the gap between theoretical knowledge and tangible applications. This collaborative synergy facilitates the translation of cutting-edge ideas into practical solutions that adeptly address the intricate challenges posed by real-world neurosurgical scenarios. However, the industry's role extends beyond innovation alone. It takes on the responsibility of ushering neurosurgery devices into the market. It is a multifaceted journey encompassing regulatory navigation, approval acquisition from bodies such as the FDA, and strict adherence to exacting quality and safety standards. Upon receiving regulatory clearance, industry players orchestrate the distribution, marketing, and sales strategies that facilitate accessibility for healthcare providers and patients. Significantly, the industry sector anchors the vital clinical validation and trials process. Through collaborative partnerships with medical professionals, industry actors meticulously conduct comprehensive clinical trials to establish neurosurgery devices' safety, efficacy, and usability. These trials substantiate the real-world benefits of the technology, instilling coincidence among regulatory bodies, healthcare practitioners, and patients and ultimately driving the adoption of innovative devices. The sector's role also encompasses the vital financial aspect of the neurosurgery devices market. Successful innovations attract diverse investments, from venture capital to corporate funding, supporting ongoing research, development, and expansion efforts. This f financial infusion propels the continuous growth and advancement of the neurosurgery devices sector. The industry sector is a transformative catalyst within the neurosurgery devices market. Through its commitment to innovation, rigorous validation, commercialization expertise, and collaborative spirit, the industry sector not only propels the evolution of medical technology but also fosters better patient outcomes, enhanced healthcare practices, and sustained growth within the broader landscape of neurosurgery.

Table A1 - which can be found in the annex - shows an array of organizations, SMEs and startups from all over the world focusing on neurosurgery devices. Our research found that the US leads the list with 52% of companies, followed by the EU, Switzerland, and the UK at 33.3%. [58]. In order to understand the environment of neurosurgical devices, it is essential to look at its professional communities and observe the actions and aims of these communities as one can benefit from their professional knowledge, medical advice, network, discussions about social issues in the workplace, discussions on patient issues, and discussions on newly released devices. While it is impractical to join and engage in every accessible community, focusing on one or two can have a positively impact on one's business.

Table 2. Renowned Professional Communities in Neurosurgery.

Name	Founded	Description
ISPN INTERNATIONAL SOCIETY FOR PEDIATRIC NEUROSURGERY	United States, 1972	Serve as a forum for communication among pediatric neurosurgeons, as well as between them and basic scientists and specialists in related fields; serve as a medium for the advancement of scientific knowledge, medical care, rehabilitation, and disease prevention in the field of pediatric neurosurgery; and promote high standards of training at an international level. UN Sustainable Development Goals: #3 Good Health and Well-being.
essfn European Society for Stereotactic and Functional Neurosurgery	Italy, 1970	Promote high-quality research and innovation in the field of stereotactic and functional neurosurgery around the world. UN Sustainable Development Goals: #3

Name	Founded	Description
		Good Health and Well-being.
	Italy, 2011	Spread minimally invasive neurosurgery all over the world. ISMINS vision is to encourage information exchange and skill advancement in minimally invasive neurosurgery in order to improve treatment results. UN Sustainable Development Goals: #3 Good Health and Well-being.
	United States, 1989	To educate, motivate, and encourage female neurosurgeons to achieve their professional and personal goals, as well as to assist neurosurgery in resolving the difficulties associated with training and retaining a diverse and balanced workforce. UN Sustainable Development Goals: #5 Gender Equality.
World Society for Stereotactic and Functional Neurosurgery (WSSFN)	France, 1963	Advance research, investigations, and procedures in stereotactic and functional neurosurgery; promote the study and teaching of improved treatment of people suffering from brain injuries, lesions, disorders, and anomalies by discovering the cause and treating the same. UN Sustainable Development Goals: #3

Name	Founded	Description
		Good Health and Well-being.
ISCoS The International Spinal Cord Society	United Kingdom, 1961	Investigate issues addressing traumatic and non-traumatic spinal cord injuries, notably advances in medical and surgical therapy and social integration of the paralyzed. UN Sustainable Development Goals: #3 Good Health and Well-being.
IFNE International Federation of Neuroendoscopy	Japan, 2001	The International Federation of Neuroendoscopy (IFNE) has numerous purposes. Among their goals is to advance neuroendoscopy locally, nationally, and internationally. They do this by representing and collaborating with all neurosurgical or sister discipline Societies in Commissions, International Organizations, and Forums.

2.2.1.1. Health technology accelerators and incubators in Europe

Health Technology Incubators and Accelerators are beneficial for startups for various reasons. Firstly, these organizations support startups by offering funding, mentorship, and access to industry experts. This support can help startups develop their products and services more quickly and effectively. Secondly, incubators and accelerators allow startups to network with other entrepreneurs, potential customers, and investors. This can help them establish partnerships and collaborations that can help grow their business. Thirdly, Health Technology Incubators and Accelerators can provide startups access to specialized resources they may not have had otherwise. This can include access to specialized equipment, laboratory space, and regulatory guidance. Fourthly, being accepted into an incubator or accelerator can provide a level of validation for a startup, which can be helpful when seeking additional funding or partnerships. Finally, these organizations can help startups to speed up the process of bringing their products and services to market, by providing them with the necessary resources, support, and expertise. Early-stage health tech entrepreneurs interested in building their startup companies might benefit from investment or advice from incubators and accelerators. According to a report published by Dealroom, Inkef Capital, and MTIP, the aggregate value of European health technology increased from $8 billion to $41 billion between 2016 and 2021. Even though investments in digital health are reaching new heights, many entrepreneurs need more means to turn their unique ideas into successful enterprises. Fortunately, incubators and accelerators may help health tech firms in their early phases [8].

The distinction between accelerators and incubators is a topic of debate, as the terms are often used interchangeably. However, there are some key differences between the two types of organizations that can be identified.

Incubators typically provide a more comprehensive range of support services to early-stage startups. This can include providing office space, mentorship, networking opportunities, legal advice, and funding. Incubators are often focused on helping startups develop their products or services from the ideation stage to commercialization. They typically have a longer time horizon than accelerators and may support startups for several years. Incubators are generally concerned with developing the concept of early-stage businesses or single entrepreneurs in order to form a business strategy. They provide mentors, office space, and legal guidance.
Furthermore, incubators provide networking chances with other founders and professionals with significant financial resources and knowledge, which aids incubate long-term success. Incubators are flexible (typically lasting six months to five years) and finish when a company has a service or product to market to investors or consumers [8].

Accelerators, on the other hand, are typically focused on accelerating the growth of existing startups. They provide a shorter and more intense support program, often lasting several months. The program may include mentorship, networking, funding, and resources such as office space and access to specialized equipment. The goal of an accelerator is to help startups achieve rapid growth and scale their businesses more quickly than they would be able to do on their own. Accelerators are concerned with the growth of a company.

They provide mentorship, supply chain resources, and investment in exchange for stock to entrepreneurs who currently have minimum viable products (MVPs). Accelerator programs are designed to help businesses grow quickly. They are often immersive, lasting 3 to 6 months to prepare an early-stage firm for market [8].

Overall, the main difference between accelerators and incubators is the length and intensity of the program offered. Incubators provide a more comprehensive range of support services over a longer period, while accelerators offer a shorter, more intense program focused on rapid growth and scaling.

Germany leads the list with three health tech accelerators and one incubator. Firstly, **Bayer G4A** is an accelerator located in Berlin with over 150 years of experience in the life sciences industry. The G4A Program is a startup accelerator that helps digital health entrepreneurs' prototype and to expand and scale their firms. The program is divided into two sections: Growth and Advance. The Growth Track program is designed for early-stage firms having an MVP that is being validated or has published findings. The Advance Track program is designed for mature firms with a marketable product. The Bayer G4A program encompasses the whole startup value chain, from concept to commercialization. Benefits include free co-working space on Bayer campuses for about 100 days, coaching from industry professionals, networking opportunities, and funding of up to €100,000. Bayer has funded over 150 digital health firms since 2013, resulting in over 30 direct collaborations. Okko Health, a health tech business building digital eye biomarkers to track visual interactions with smart gadgets, and Chorus Health, which develops and distributes application software for specialized women's care, are both successful alumni of Bayer.

Startupbootcamp Digital Health Berlin, another accelerator with a time length of 3 months is backed by healthcare sector leaders such as Sanofi, Munich Re, Berlin Institute of Health, Deutsche Apotheker und rztebank, Vilua, and counts with legal counsel from Dentons. To scale their health tech firms, selected entrepreneurs work with over 150 mentors, partners, and investors. Participants receive €15,000 in cash to cover living expenses during the program, free office space, and more than €700,000 in exclusive partner arrangements from prominent technology companies such as Amazon, HubSpot, SendGrid, and others. BOCA-Health, which developed a portable gadget that measures the hydration state of patients suffering from body water imbalances, was expedited by Startup bootcamp digital health. Goodsomnia is another Alumni firm that provides a stop-snoring equipment and software solution to detect, analyze, and treat snoring using comprehensive electroencephalogram (EEG) screening.

Merck’s Innovation Accelerator is located in Darmstadt, Germany, and lasts 3 months. Merck's Innovation Accelerator chooses emerging scientific and technology businesses addressing one of Merck's strategic emphasis areas each year from more than 500 applicants: bio-sensing and interfaces, liquid biopsy, clean meat, or artificial intelligence-enabled health solutions. For three months, selected teams receive individual support and mentoring from experts across the Merck global network and funding of up to €50,000. Teams can also extend their participation in the program by joining the Merck China Innovation Hub in Shanghai. Syrona Health, a tailored digital health platform for chronic gynecological and uterine disorders, is Merck’s alumnus.

Flying Health is located in Berlin, Germany. In 2016, Flying Health was introduced as the leading ecosystem for next-generation healthcare. The two-year Incubator program focuses on digital health product market entry. It advises industry leaders and entrepreneurs and provides a unique environment for health tech businesses to form profitable alliances and gain market access to digital diagnostic and therapeutic applications. Flying Health's mission is to assist companies by leveraging their expertise, network, and experience. Flying Health has incubated Kaia Health, which provides digital programs to those suffering from chronic musculoskeletal pain, and Clue, a period and cycle tracking software.

The United Kingdom, Italy, Sweden, Holland, Denmark, and Hungary each have a single accelerator.
Digital Health. London Health tech accelerator aims to accelerate digital transformation in London's National Health Service (NHS), alleviating service strain and empowering people to control their health. Over 12 months, the program works with up to 20 high-potential small and medium-sized firms, providing customized support and guidance, expert-led seminars and events, and facilitating linkages between innovators and NHS organizations facing specific difficulties. Digital Health London connects businesses to funding opportunities but does not provide or guarantee direct funding. They make no investments, nor do they take any equity. Since 2016, the Digital Health London Accelerator has supported 122 digital health companies, with 87% demonstrating growth while on the program. Infinity Health, a digital platform where staff can log, communicate, and coordinate their work in real-time, is a successful Alumni. Babylon Health, a digital and virtual healthcare service that integrates artificial intelligence with human medical experience to link patients and doctors, has also been expedited by Digital Health London.

Open Accelerator, located in Milan, Italy, founded in 2016 and supported by ZCube, a Zambon's Research Venture firm, is a program that takes place for 3 months and is devoted to digital solutions that use cutting-edge technology such as wearables, biomarkers, sophisticated analytics, and artificial intelligence. Participants can connect with a global network of entrepreneurs, scientists, investors, venture capitalists, and professionals. The most substantial projects will receive a milestone-based seed investment of up to €100,000 per project and €25,000 in services at the end of the acceleration phase. Among its alums, Caura (previously known as CortiCare) is creating a portable and intelligent device for hormonal testing. Biorek is developing a kit for diagnosing and prognosis of kidney cancer using only a liquid sample. The company's kit is designed to gather blood and urine samples, allowing healthcare providers to identify renal cell carcinoma biomarkers, thereby aiding in patient's detection and prognosis of kidney masses.

Health2B is an entirely virtual health tech accelerator in Lund, Sweden that helps early-stage entrepreneurs in digital health, mobile health, e-health, the internet of things, wearables, lifelog, biohacking, and quantified self. The program accepts applications from businesses from all across the world and selects eight companies each year. For ten weeks, participants validate their business idea with the help of mentors, industry experts, and personalized 1:1 coaching. The value of assistance and coaching exceeds €40,000. The program is free, with 40 Alumni firms in six batches, and companies retain 100 percent of the equity. Neki, a GPS tool for the elderly patients with dementia, and Luxheal, a virtual coach for customized care for myocardial infarction patients, are among the startups accepted into the accelerator.

Rockstart Health, founded in 2011, is a health tech accelerator that takes place for a year and is located in Nijmegen, Holland, that focuses on market-validated health firms. By linking companies with partners, investors, and mentors, the program gives them access to finance, market, and expertise. Rockstart Health also develops tailored programs to foster collaboration between startups and corporations, resulting in speedier access to co-creation, commercial relationships, and funding. Startups accepted into the Rockstart Health Program receive
€20,000 plus €75,000 in-kind funding in exchange for a convertible loan with a 6 percent ownership stake. Since its establishment, Rockstart has invested in over 200 businesses, assisting them in raising over €89 million and employing over 700 employees. BrainTrip, an EEG-based system for diagnosing early-stage dementia, and Cardiomo, a cardiac monitor for remote patient

monitoring, are also alumni.

Accelerace Medtech Health Care is an equity-free initiative that assists Denmark's most promising entrepreneurs in preparing for rapid growth and funding. It is located in Copenhagen, Denmark, and has a time length of 5 months. The benefits include extensive 1:1 training and mentoring from Danish biotech ecosystem professionals, the business community, and worldwide experts. Selected startups also receive exclusive access to investment through Accelerace's network of prominent investors, investor programs, or its fund. Accelerace has invested in over 69 firms that have completed the Accelerace program and formed relationships with Maersk, Novo Nordisk Foundation, Arla, Foss, NRGI, Business Lolland- Falster, Bang & Olufsen, SE, Endesa, and Enel. Throughout the year, applications are accepted for the program. Biogenity, a data-driven biotech business that provides a wide range of proteome research services, and EvoPlexus Medics, which focuses on precision medicine and customized healthcare using machine learning and artificial intelligence, are among those taking part.

Health Venture Lab, headquartered in Budapest, is an international network of healthcare innovation players supported by GE Healthcare. Participants in the Reactor 2021 project get insight into the marketing and development of their technologies by tapping into the knowledge of industrial and academic partners. Four rigorous remote Sprints combined with coaching throughout a 6-month acceleration program provide teams with substantial training and the experience needed to commercialize their product or service. Health Venture Lab does not invest in its cohorts' businesses or fund entrepreneurs. They focus on delivering customized mentorship, education, and training to help businesses grow and scale their technologies. Among the successful Alumni are Xvision, which utilizes artificial intelligence to automate radiography analysis, and Vitadio, a web and mobile application that provides customized digital therapies to type 2 diabetic patients.

In conclusion, all of them are excellent choices for neurosurgery startups, but Bayer G4A and Health Venture Lab accelerators set themselves apart. It also depends on the individual needs of the startup and the stage they are in. Bayer G4A stood out as it had over 150 years of experience in the life sciences industry and has two tracks for innovation to meet the needs of any startup. In addition, they provided coaching from industry professionals, networking opportunities, and funding of up to 100,000 Euros. Health Venture Lab is made up of an international network of healthcare innovation competitors supported by GE Healthcare. They provide participants in the program with insight into marketing and development from industrial and academic partners. They provide training to commercialize participant company's products or services. Finally, what made them unique is that they delivered customized mentorship to help businesses grow and scale their technologies.

2.2.2. Academia

The academia part of the four-helix model represents the academic institutions, including universities, research centers, and other educational organizations. The academic sector plays a crucial role in developing new knowledge, ideas, and technologies and is responsible for training the next generation of professionals and researchers. Stakeholders that typically make up the academia sector include professors, researchers, students, and administrative staff who work together to generate new knowledge through research and experimentation. In addition, academic institutions are responsible for providing education and training to students in a wide range of fields, from science and technology to humanities and social sciences. Academia also plays a critical role in promoting innovation and entrepreneurship, since they can foster innovation by encouraging collaboration and interdisciplinary research, providing resources and funding for startups and new businesses, and promoting entrepreneurship education and training. Moreover, academic institutions often collaborate with other stakeholders in the four-helix model, such as businesses and government agencies, to address complex social, economic, and environmental challenges. For example, academic researchers may work with businesses to develop new products or technologies or partner with government agencies to provide expertise and support for policy development and implementation. Academia provides a powerful research engine for neurosurgery device businesses to tap into and, in turn, provides financial aid and development and manufacturing skills to enable commercialization. In addition, worldwide academic actors such as universities and research labs have a strong presence and contribute much time to research, producing novel technologies and making scientific breakthroughs through PhDs, collaborative research between universities, and other research activities. On one hand, academic institutions conduct research to advance the understanding of neurological disorders, develop new surgical techniques and devices, and improve patient outcomes. Below are some of the most renowned institutions in this niche.

University College of London: Brain Surgery with Robotics, AI and Neuronavigation. The BRAIN group is an interdisciplinary collaboration between National Hospital for Neurology and Neurosurgery surgeons and engineers at the ESPRC Centre for Interventional and Surgical Sciences (WEISS).

UCL aims to develop and apply novel technology to make neurosurgery safer and more effective for patients, simpler for surgeons, and more efficient for healthcare systems, including those in resource-limited settings [10]. Figure 7 shows the research areas in the BRAIN group.

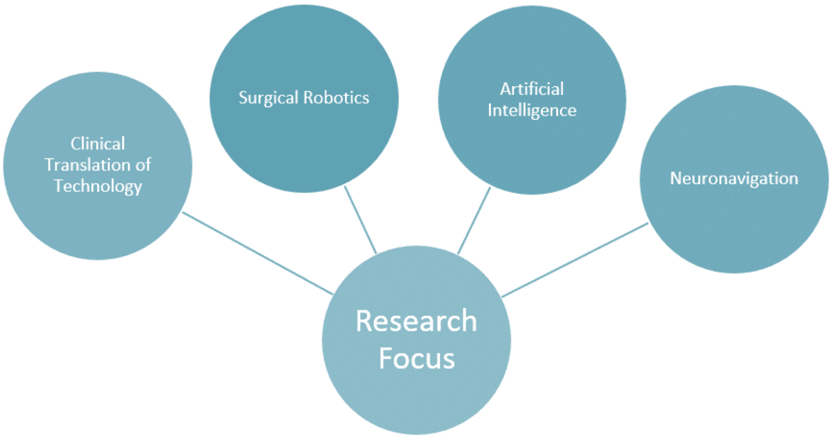

Figure 7. UCL BRAIN Research Focus Areas [10].

Universidad Miguel Hernández: The medical robotics group is a multidisciplinary team dedicated to advancing robotic technology in health and surgery and specializes in creating wearable electronics for monitoring biometric parameters and the application of artificial intelligence (AI) techniques for early pathology detection and user quality of life improvement. In the surgical field, they are developing innovative intraoperative medical imaging systems based on RF and US for image-guided robotic surgery. UMH has four research lines, surgical robotics, image-guided surgery, wearable health electronics, and diabetes technology. The ones relevant to this report are surgical robotics and image-guided surgery [12].

KU Leuven: The RAS-group is dedicated to designing and developing advanced technological, robotics-empowered instruments to assist the surgeon in the operating room [11]. The catalogue of the main research topics at RAS group are included in Figure 8. They are currently working on the following projects:
FAROS: Functionally Accurate Robotic Surgery (robotic spine surgery)
ARTERY: Autonomous Robotics for Transcatheter delivery systems

GIFT-Surg: Guided Instrumentation for Fetal Therapy and Surgery
ATLAS: Autonomous Intraluminal Surgery

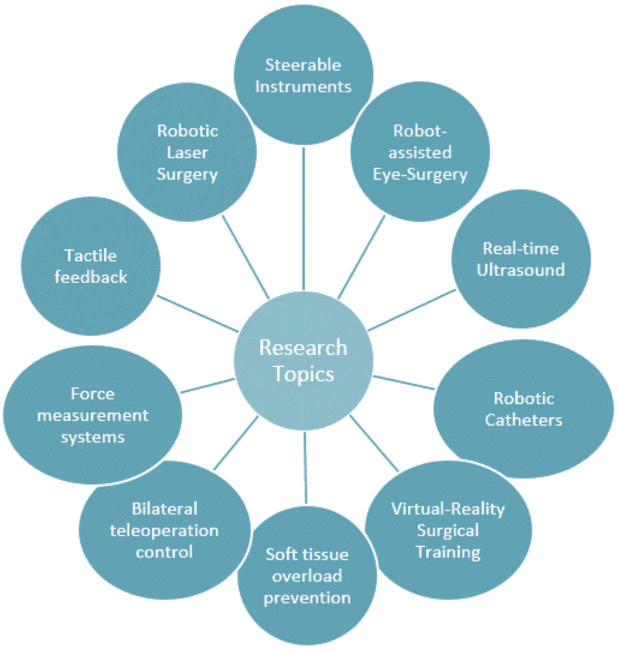

Figure 8. Research Topics at RAS-group [11].

Duke University: Duke University has introduced a new training program to encourage Ph.D. students to create the next generation of intelligent robotic surgical equipment. The Traineeship in the Advancement of Surgical Technologies (TAST) program will offer graduate engineering and computer science students the opportunity to design improvements in fundamentally new technologies to advance surgical practice. These new surgical devices will consider provider, societal, end-user, and patient needs by enlisting interdisciplinary expertise across Duke's campus in areas such as law, ethics, global health, and industry partners [13].

Imperial College London: The Hamlyn Center at Imperial College London focuses on four research areas within robotics. Surgical robotics, assistive robots, micro/nanorobots, and BCIs [14]. The main research area concerning this market analysis is the surgical robotics research area, which focuses on developing lightweight, cost-effective, flexible manipulators with a small footprint in the operating room. These surgical robots are inherently complicated and clever, yet they are accessible, lightweight, and natural, with seamless user control. They should improve the current surgical workflow rather than drastically modify it or make typical procedures more difficult. To that aim,

they are now developing a new generation of miniaturized and sophisticated mechatronic devices and robots for flexible access surgery and looking into novel
approaches for providing synergistic control between the surgeon and the robot. The research themes are a Hyper-redundant snake robot for flexible access surgery, innovative hand-held instruments, a continuum robot, perpetual docking for robotic control, cooperative robotic control, and dynamic, active constraints [14].

Mayo Clinic: The Precision Neurotherapeutics Innovation Program is a one-of-a-kind collaborative effort across many fields to develop personalized treatments for persons with neurological illnesses utilizing simulation science. It collaborates with bioengineers at Arizona State University to use robotic brain-computer interface devices. It is an active cooperation
between Bernard R. Bendok, M.D.'s Neurosurgery Simulation and Innovations Laboratory, and Kristin R. Swanson, Ph.D.'s Mathematical Neuro-Oncology Laboratory. The program's objective is to use innovative, individualized mathematical modelling and neural bioengineering approaches to improve the lives of people suffering from neurological illnesses [15].

McGovern Medical School: The Microsurgical Robotics Laboratory focuses on creating next- generation robotic systems for microsurgery to treat endovascular illnesses such as cerebral stroke and other life-threatening conditions such as fetal deformities and brain abnormalities. Miniaturized devices can pass through small, thin, and branched blood arteries in the brain and access deep places in the body that are now inaccessible with traditional surgical techniques. Patients living in distant areas where unique surgical treatments are not readily available can be treated remotely using microsurgical robotic instruments. Hence, they focus on three research projects. Firstly, steerable robotic microcatheters for cerebral stroke intervention. Secondly, microsurgical robotics for fetal, brain, and endonasal surgery, and the last one focuses on image-guided, robot-assisted surgery [16].

University of Twente: The Surgical Robotics Lab (SRL) creates a variety of flexible, minimally invasive surgical instruments and micro-robotic systems. It controls them robotically using clinical imaging modalities such as ultrasound, computed tomography, and magnetic resonance images. SRL is made up of an interdisciplinary team of engineers from many disciplines. They work with clinical partners at the University Medical Center Groningen, the Radboud University Nijmegen Medical Center, and Medisch Spectrum Twente [17]. The European Commission (Horizon, 2020), the European Research Council (ERC), the Netherlands Organization for Scientific Research (NWO), the Dutch Technology Foundation (STW), the Netherlands Organization for Health Research and Development (ZonMw), the Netherlands Enterprise Agency (RVO), and the Northern Netherlands Provinces Alliance all generously support SRL (SNN) [17].

NERO Project: The NERO project (Figure 9) has assembled a strong team of researchers who are eager to turn the concept of a neurosurgical robot into a market-ready product. The NERO project, which is being implemented in Croatia, is creating an innovative, automated robotic system for performing neurosurgery procedures. It is intended to be simple, compact, and economical, allowing surgeons to work more quickly, safely, and correctly than previous models. "I am deeply convinced that after this project is completed, Croatian robots will perform surgery on patients worldwide in surgical rooms. Thus, along with other bright examples in the Croatian economy, which have become increasingly common in recent years, it will help present Croatia in a very different and positive light." Bakić, NERO project manager [18].

Universidad Politécnica de Madrid: UPM is one of the largest research centers in e-Health in Spain. The LifeSTech research group and the Centre for Automation and Robotics (CAR) are critical participants in developing robotics for healthcare and other fields. Life Supporting Technologies (LifeSTech) is a research, development, and innovation group dedicated designing, developing, and evaluating services and applications based on ICT (Information and Communication Technologies) [60]. The group houses a living lab dedicated to technologies for health and wellbeing. UPM works on four key areas in this lab - Robot Hall, Smart Home, Maha Lab, and Future Health. The Centre for Automation and Robotics (CAR) has four research lines: intelligent robotics, applied robotics, intelligent monitoring and control, and perception. Field & Service Robotics, Robotics & Cybernetics, and Neural & Cognitive Engineering are three research groups in CAR that may benefit companies in the field of robotic neurosurgery. To learn more about LifeSTech and CAR's research lines, please refer to Annex A5.1 and A5.2.

In conclusion, although academia seems to be making some significant breakthroughs in surgical robotics and branching into many of its advantages (i.e., assistive robots, virtual reality surgical training, robotic catheters, neuronavigation), the number of institutions is relatively small. Consequently, their research may have a limited impact compared to research conducted by large medical device companies.

2.2.3. Medical devices government regulators

The Government helix of the model seeks to promote innovation and collaboration across different sectors. In the context of the neurosurgical market, the Government plays an essential role in regulating the industry, promoting public health and safety, and supporting research and development. The stakeholders that make up the Government may vary depending on the specific context, but they typically include elected officials, government agencies, and regulatory bodies. Regulatory bodies for neurosurgical markets may vary by country, but here are some examples of regulatory bodies worldwide:

1. Food and Drug Administration (FDA): The FDA is a regulatory body in the United States responsible for ensuring the safety and effectiveness of medical devices and drugs, including those used in neurosurgical procedures.
2. European Medicines Agency (EMA): The EMA is responsible for evaluating and supervising the safety and efficacy of medicines in the European Union, including those used in neurosurgical procedures.
3. Therapeutic Goods Administration (TGA): The TGA is an Australian government agency responsible for regulating therapeutic goods, including medical devices and drugs used in neurosurgical procedures.
4. Pharmaceuticals and Medical Devices Agency (PMDA): The PMDA is a regulatory agency in Japan responsible for overseeing the safety and efficacy of medical devices and drugs used in neurosurgical procedures.
5. Health Canada: Health Canada is a regulatory agency responsible for ensuring the safety and efficacy of medical devices and drugs used in neurosurgical procedures in Canada.
6. China Food and Drug Administration (CFDA): The CFDA regulates the safety and efficacy of medical devices and drugs used in neurosurgical procedures in China.

Elected officials, such as members of Congress, governors, and mayors, are responsible for setting policy priorities and allocating resources to support public health and safety initiatives, including those related to neurosurgical research and development. Government agencies, such as the National Institutes of Health, the Food and Drug Administration, and the Centers for Medicare and Medicaid Services, are responsible for regulating the neurosurgical industry, providing funding and support for research and development, and developing policies to promote public health and safety. Regulatory bodies, such as state medical boards and professional associations, are responsible for ensuring that medical professionals meet high standards of competence and ethical conduct. The Government collaborates with other stakeholders in the Four Helix Model to promote innovation and advance the neurosurgical market. For example, the Government collaborates with academic institutions to fund research and development, promote public awareness of neurological disorders, and facilitate policy development and implementation. The Government also collaborates with the industry to support developing and commercializing new neurosurgical products and services, regulate the industry to ensure public safety, prevent fraud, and promote global competitiveness.

Figure 1 (*World medical device market by region – 2020)* shows the prevalence of the USA and Europe in terms of market weight. Not only that but also the US and European medical device regulators have more strict guidelines than the rest of the world. Therefore, what is approved in the US or EU will likely be approved elsewhere. In the **European Union**, medical devices are regulated at the EU Member State level, but the European Medicines Agency is involved in the regulatory process. Manufacturers can place a CE (Conformité Européenne) mark on a medical device once it has passed a conformity assessment. The EMA is in charge of assessing the quality, safety, and efficacy of marketing authorization applications examined through the centralized system and the safety and performance of a medical device concerning its usage with a medicinal product [19].

In the **United Kingdom**, the Medicines and Healthcare Products Regulatory Agency (MHRA) conducts market surveillance of medical devices in the UK market and has the authority to judge device marketing and supply. The MHRA designates and oversees UK conformity assessment bodies [20].

In **Canada**, before approving the sale of a medical device, the Medical Devices Directorate (MDD) ensures that it meets the Food and Drugs Act and its Regulations for safety, effectiveness, and quality [21]. The MDD also collaborates with other organizations to examine the dangers of medical devices and make regulatory choices to manage those risks.

Regarding the **United States**, the FDA's Center for Devices and Radiological Health (CDRH) regulates companies that manufacture, repackage, relabel, and import medical devices for sale in the United States. CDRH also monitors radiation-emitting electronic items (both medical and non-medical), such as lasers, x-ray systems, ultrasound equipment, microwave ovens, and color televisions [22]. Table A1 in the Annex shows recent community partners of the FDA related to the EBRAINS work area.

2.2.4. Civil Society

According to the World Bank: "*Civil society (…) refers to a wide array of organizations: community groups, non-governmental organizations [NGOs], labor unions, indigenous groups, charitable organizations, faith-based organizations, professional associations, and foundations.*" Within the Four Helix Model, civil society is a crucial force shaping the dynamics of the neurosurgery devices market. Comprising non-governmental organizations, patient advocacy groups, and community-based entities, civil society exerts a profound influence by championing patient-centric innovation, advocating for ethical considerations, and fostering transparency. These groups play a pivotal role in representing patients, healthcare professionals, and the public, ensuring that the development and deployment of neurosurgery devices align with ethical standards, patient safety, and societal needs. Through regulatory engagement, information dissemination, and educational initiatives, civil society facilitates informed decision-making, promotes equitable access to innovative technologies, and drives a dialogue that steers research priorities toward addressing pressing clinical and patient concerns. The case for public participation has become increasingly compelling over the years. There are three justifications for this [23]:

1. Participation as a means of achieving more effective services or public health programs that are more responsive to individual needs.
2. Self-determination as a health objective. Participation is regarded as a process as well and an outcome in this context, leading to improved individual or community empowerment and citizen control.
3. Justifications based on rights, emphasizing democratic values and citizenship. These rights include citizens' rights to participate in health care and have a collective voice in health planning.

In professional-driven health systems, the role of communities and their potential benefit are only sometimes recognized. However, this must alter if sustainable health systems that work for everyone are to be built. Here are some of the benefits of community-based approaches:

1. Active involvement in healthcare and community networks allows for more local representation and leadership. Hence, involvement in mental health and its networks is essential in this case.
2. Engaging with communities such as neurosurgery, mental health, and mental diseases that may require neurosurgery allows for a better understanding of local needs and ambitions.
3. With the rising use of personalized technology in public service delivery, services must be better tailored to the demands of users. Therefore,

these services can be wellness or mental health applications to suit the demands of specific civil societies.

4. Community engagement can help directly address social exclusion and mental health disparities. Therefore, for the individual to not be vexed by their condition, they can identify with people with a similar state by getting involved in these civil societies.

Community participation increases local accountability and community ownership opportunities by facilitating them. The Global Civil Society Database [24] illuminated desired global societies. By quickly searching the database, other societies in this domain or any other domain can be identified. Table 3 below showcases some neuro-health societies for neurological disorders worldwide.

Table 3. Global Neuro-health Societies for Common Neurological Illnesses

Name	Founded	Description
IBE International Bureau for Epilepsy	Italy, 1961	Collect and disseminate information and experience about the care and social problems of people with epilepsy; offer information on how to develop and fund laity groups. UN Sustainable Development Goals: #3 Good Health and Well-being.
IBIA International Brain Injury Association	United States, 1992	Create and support a multidisciplinary team of medical and clinical specialists, family members, survivors, and others who work to enhance outcomes, opportunities, and successes for those who have had a brain injury. UN Sustainable Development Goals: #3 Good Health and Well-being.

Name	Founded	Description
World Stroke Organization	South Africa, 2006	Raise awareness about stroke prevention and treatment. UN Sustainable Development Goals: #3 Good Health and Well-being.
WFMH World Federation for Mental Health	United Kingdom, 1948	Promote the best attainable level of mental health among all peoples and nations, as defined in the widest biological, medical, educational, social, and cultural parameters.
ISBD	United States, 1999	Promote bipolar disorder awareness, education, and research in all facets.
Dementia Alliance International The global voice of dementia	United States, 2014	Advocating for and supporting people with dementia; promoting dementia education and awareness to help dispel myths and eliminate stigma and discrimination; improving the quality of life for people with dementia, their families, and care partners; advocating for human and legal rights for all people with dementia and dementia as a disability. UN Sustainable Development Goals: #3 Good Health and Well-being, #10 Reduced Inequalities, #16 Peace, Justice, and Strong Institutions, #17 Partnerships for the Goals.
GIP Federation Global Initiative on Psychiatry	The Netherlands, 1980	Promote compassionate, ethical, and effective mental health treatment worldwide; assist a global network of persons and groups in developing, advocating for, and implementing required reforms; and struggle against

Name	Founded	Description
		political abuse of psychiatry wherever it occurs. UN Sustainable Development Goals: #3 Good Health and Well-being, #5 Gender Equality, #10 Reduced Inequalities, #16 Peace, Justice, and Strong Institutions.
International OCD Foundation	United States, 1986	Educate the general public and professionals about Obsessive Compulsive Disorder (OCD) in order to raise awareness and improve treatment quality; support research into the causes of, and effective treatments for, OCD and related disorders; improve access to resources for those with OCD and their families; advocate and lobby for the OCD community. UN Sustainable Development Goals: #3 Good Health.
GLOBAL AUTISM PROJECT	United States, 2003	Promote global acceptance and integration of people with autism through training communities in culturally suitable, long-term practices. UN Sustainable Development Goals: #3 Good Health.
International Parkinson and Movement Disorder Society	United States, 1985	Disseminate knowledge about movement disorders; encourage research, prevention, and treatment of movement disorders; and develop and support public policy that will impact patient care. UN Sustainable Development Goals: #3 Good Health.

Name	Founded	Description
International League Against Epilepsy	United Kingdom, 1909	The International League Against Epilepsy supports research in epilepsy, including its causes, diagnosis, treatment and prevention. UN Sustainable Development Goals: #3 Good Health.
SOBP Society of Biological Psychiatry	United States, 1945	Promote research in the field of biological psychiatry, with a focus on understanding the biological underpinnings of psychiatric disorders. UN Sustainable Development Goals: #3 Good Health and Well-being.

3. Neurosurgery Innovation Areas

Neurosurgery is a rapidly evolving field, with new technologies and techniques constantly developed to improve patient outcomes. The following section of this report will elaborate on the neurosurgery device market sub-areas that stand out for their growth rate and impact on society. An analysis on their instrumentation and market value will follow. These neurosurgery medical device innovation areas were selected according to their current market worth, compound annual growth rate, and necessity.

3.1. Neuroendoscopy

A *neurological endoscope* is a light-emitting device that looks inside the brain's ventricles [77]. The evolution of neuroendoscopy has occurred in four distinct stages. The first endoscopic procedure on the brain was performed by L'Espinasse about a century ago in 1910. He attempted endoscopic choroid plexus coagulation to treat a hydrocephalic patient. Dandy and Mixter explored endoscopic fenestration of the third ventricle for the treatment of hydrocephalus in the 1920s and 1930s, ushering in the next phase of neuroendoscopy [25]. The early 1970s saw the third significant advancement in neuro endoscopy. Technological breakthroughs in optics and electronics enabled the development of both flexible fiber and high-resolution rigid endoscopes for usage within the ventricles [25]. The present stage of neuroendoscopy has been the boom of endoscopic third ventriculostomy for hydrocephalus therapy and endoscope-assisted minimally invasive surgical techniques that began in the 1980s and 1990s and continues to this day [25]. Neuroendoscopy adheres to a general trend in neurosurgery of diagnosing disease with minimally invasive procedures to decrease approach- related trauma and improve pathological visualization.

3.1.1. Instrumentation

The surgeon needs a specific neuroendoscopy setup to achieve the best surgical results. Furthermore, recording equipment that captures images in video or digital format for later study is required. The endoscopic tower should comprise the following components: a video camera, camera control units, a light source, a video recorder, a video display, and a computerized system for storing video segments or capturing single images. Endoscope placement and fixation arms attached to the operating table or headrest assist the surgeon in avoiding arm fatigue. A pair of grasping forceps and scissors, a coagulation device (monopolar or bipolar), an irrigation system, and a straight and 30°-angled scope are among the endoscopic devices (see Figure 10) [25]. Furthermore, a trained helper is required so that the surgeon can work two-handedly. Frameless computerized neuronavigation is increasingly being employed in intracranial endoscopic neurosurgery and has been demonstrated to be accurate, reliable, and beneficial in certain intracranial neuro endoscopic operations to increase endoscopic approach accuracy [25].

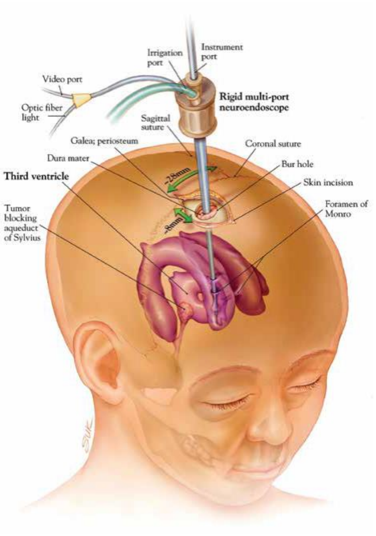

Figure 9. Endoscope, light source, camera, and irrigator for intraventricular surgery are the essentials of endoscopy [27].

3.1.2. Market

The global neuroendoscopy devices market was worth USD 117.5 million in 2018 and is expected to be worth USD 204.4 million by 2026, growing at a 7.12% compound annual growth rate (CAGR) [26].

The markets for all the identified innovation areas are growing due to three main factors: the growing incidence of neurological diseases, the aging population, and the increasing number of neurosurgeries performed. These are the common factors that boost the market in each area. The population has been gravitating toward minimally invasive procedures, including neuro endoscopy. This is due to the benefits offered to patients, such as reduced recovery time, smaller incisions, reduced hospital stay, less post-surgery trauma, and fewer complications during surgery. There is also the growing elderly population because, in many instances, older adults cannot undergo traditional surgery. Therefore, neuroendoscopy is the clear path for them. Finally, the rising adoption of rigid endoscopes because they generate higher quality pictures and allow for more straightforward instrument passage when compared to flexible endoscopes [26]. The increasing prevalence of brain tumors [27], the growing number of neurosurgeries, and technological advancements in neuroendoscopy are clear motivators for the rising adoption of neuroendoscopy.

B. Braun, Aesculap, and Karl Storz are a few of the leading firms functioning globally regarding neuroendoscopy equipment market revenue. Regarding neuroendoscopy equipment, these companies control a sizable piece of the market in the United States. Ackermann Instrumente GmbH., Adeor Medical AG, Clarus Medical LLC, Machida Endoscope, Tonglu WANHE Medical Instrument, HAWK, Schindlerendoskopie Technologies GmbH, and others are among the key competitors operating in the global market [26]. The neuroendoscopy devices industry is highly fragmented, with numerous entrepreneurs joining the market in recent years.

3.1.3. Further remarks

As stated previously, neuroendoscopy offers advantages to neurosurgeons, including enhanced light intensity for better image quality, sharper images for close-up visualization, and a wider viewing angle to prevent damage during navigation. Its primary goal is to minimize brain manipulation and retraction, making it beneficial for treating deep-seated lesions in confined spaces. This approach can result in improved postoperative outcomes, shorter hospital stays, and fewer complications for specific surgical procedures.

Further advances in optical physics, electronics, and robotics will likely impact endoscopic neurosurgery. Specific endoscopic system implementations will likely pave the way for extraordinary progress in less invasive surgery. This is due to robotic surgery (Figure 10), downsizing of surgical technologies, advances in 3D and multiport endoscopy, and novel surgical design instruments.

Figure 10. The Rosa One Brain robot has been utilized for numerous neurosurgical procedures, including neuroendoscopy [78].

Future advancements in flexible endoscopes and wireless capsule or camera technologies may reduce the reliance on rigid rod lenses. Endoscopes with rigid variable view lenses will provide the most optimal characteristics when used with modern instruments and indicators. The ability of a moveable optic lens to extend the visual field may allow a neurosurgeon to use customized keyhole methods to treat disorders in fewer surgical corridors with less trauma and more efficacy [27].

3.2. Implantable Drug Delivery Systems

therapeutic drugs or medicines into the bloodstream or to specific tissue sites. Therefore, replacing the daily injection of drugs required for pain relief and treating various conditions and diseases such as osteoporosis, heart disease, cystic fibrosis, glaucoma, age-related macular degeneration (AMD), diabetes, refractory epilepsy, and cancer [28].

Recent Biomedical engineering research has focused on understanding the functional hurdles to effective drug administration. These hurdles include drug delivery in the circulatory system and drug transport across cells and tissues. The increasing global use of these devices can be attributed to the advent of enhanced technology for effectively delivering drugs to the target site. This technology also reduces adverse effects and the surge in demand for novel and innovative products [29].

3.2.1. Instrumentation

Implantable DDS are primarily made up of a micro pump with a reservoir containing the pharmaceutical drug in gaseous or liquid form. They also include an actuator release or pump mechanism, inlet and outlet valves, and, in some instances, a cannula or catheter to direct drug delivery to a target site. In the DDS, medicine is released by either a passive or active (responsive) micro pump. A standard passive actuator is based on a medication infusion technique in which the medicine is given slowly through a porous membrane or a biodegradable membrane that dissolves over time. Other passive ways include several small sealed drug containers that comprise the reservoir. Each seal releases a specific drug dose when dissolved by electrical input. The released medicine diffuses into the intended delivery site in either circumstance [28]. From the list of the top ten companies in neurosurgery, two of Medtronic's' products have been identified, the SynchroMed™ II intrathecal pump and the drug infusion pump.

Figure 11. MyPTM, N'Vision Clinician Programmer, and SynchroMed II Programmable Infusion Pump comprise the SynchroMed II Infusion System [28].

The SynchroMeds II Infusion System immediately administers pain medicine to the intrathecal region around the spinal cord. Pain therapy for severe chronic nonmalignant pain (CNMP), spinal or cerebral origin spasticity, and primary or metastatic cancer treatment are among the treatments available. The SynchroMeds II Infusion System, depicted in Figure 11, comprises the myPTM

(Personal Therapy Manager), the N'Vision Clinician Programmer, and the SynchroMeds II Programmable Infusion Pump [28].

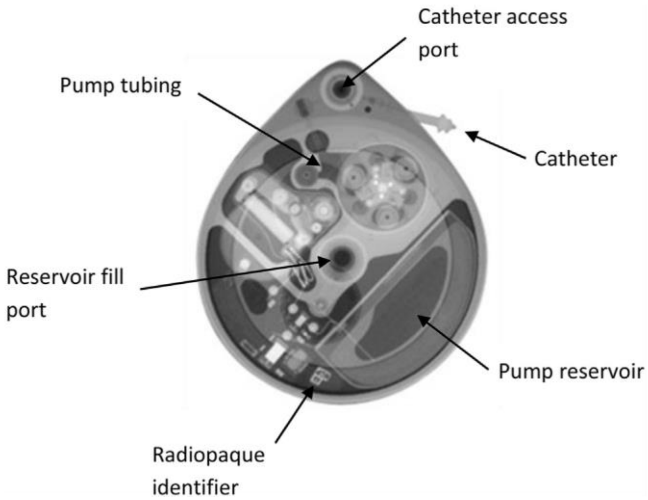

Figure 12. SynchroMed II Programmable Pump [28].

The SynchroMed II Programmable Infusion Pump (Figure 12) is placed in the abdominal cavity and is linked to a thin catheter placed in the intrathecal space. There are two sizes of medication reservoirs available: 18 and 20 mL. Depending on usage, battery life ranges from 4 to 7 years. The pump shuts down automatically after 7 years [28].

3.2.2. Market

The Global Drug Delivery Systems market is expected to reach USD 45.20 billion by 2027 at a

6.8 percent CAGR [29]. It is imperative to note that this is the general drug delivery systems market, not just focusing on applications in neurosurgery. Therefore, the actual CAGR would be lower. Companies in the industry are continually focusing on strategies such as collaboration, creation and release of new products [29]. These tactics assist businesses in increasing their income, hence pushing the total market growth.

Introducing novel products with enhanced safety and user-friendliness will likely entice large pharmaceutical businesses. Furthermore, improved dosage characteristics complement pharmacological treatment outcomes and expand the possibility of illness management in home care settings. For example, Ypsomed announced YpsoMate in November 2021, claiming it to be the world's first auto-injector for prefilled syringes with an integrated connection. It is suitable for self-administration. Furthermore, industry players are increasingly collaborating with pharmaceutical companies to develop and launch products. KINDEVA DRUG DELIVERY, for example, joined Cambridge Healthcare Innovations Limited (CHI) in April 2021 to develop and commercialize CHI's Aeolus dry-powder inhaler (DPI) platform technology [29].

The increased shift of patients toward advanced products is attributable to lower variability in systemic medication concentrations and the capacity to administer a drug accurately to a specific spot. Patients are increasingly using self-administered devices as a result of these qualities. Furthermore, digitizing medical equipment has raised patient awareness of modern medical devices. The digitalization method offers several benefits, including needle-free injection, regulated dose, and increased self-administration flexibility, resulting in increased device acceptance [29]. Medtronic announced the release of Efficio, cloud-based data management software designed for use with the SynchroMed II intrathecal drug delivery device, in January 2020. This program enabled clinicians to manage their targeted drug delivery strategies more efficiently for patients suffering from chronic pain, cancer pain, and severe spasticity.

Patient preferences for advanced products, combined with government efforts to raise public awareness of the devices, are expected to lead to market growth in the future. According to the WHO, between 2015 and 2050, the fraction of the global population over 60 will nearly double, from 12% to 22% [61]. The fact that such a high proportion of the senior population is susceptible to chronic diseases is likely to promote the uptake of such systems. Furthermore, the increased launch of innovation-driven products and digitalization in the healthcare sector has created the potential for growth for companies. Companies such as BD, Baxter International, Inc., Gerresheimer AG, and West Pharmaceutical Services, Inc. dominate the market. These companies will continue to dominate the market in the following years, owing to a diverse product portfolio and a broad distribution network. Becton, Dickinson, and Company introduced the BD Intevia 1mL two-step disposable auto- injector in October 2019, a sturdy platform device that combines an auto-injector and a pre- fillable syringe in a single integrated system [29]. Companies are emphasizing acquisitions in order to have a variety of these systems, in addition to developing a robust distribution network. For example, in May 2020, Altaris Capital Partners acquired 3M's Drug Delivery Systems (DDS) division and rebranded it Kindeva Drug Delivery. The company has over 50 years of experience in pharmaceutical development, commercialization, and contract manufacturing services in the inhalation, nasal, transdermal, and microneedle domains. Other key participants in this industry include 3M, Ypsomed, PCizer, Inc., and Nemera.

3.2.3. Further remarks

Various regulatory approval processes are suspected for technologically improved medicine delivery devices. Because these technologies are introducing breakthroughs, governing organizations have made significant efforts to assess the performance and safety of these devices. The ongoing improvement of innovative medicine delivery systems has also significantly raised the burden on federal agencies regarding product classification and evaluation [29]. For example, in November 2019, the United States Food and Drug Administration (FDA) provided a draft guideline on the product development and regulatory approval procedure for topical and transdermal administration systems. This could be a problem for companies significantly progressing in the product's development phase.

Recent product recalls attributed to software malfunctions have also pushed regulatory bodies such as the European Agency and the Food and Drug Administration to adopt stringent guidelines for approving drug delivery systems. These prominent variables may hinder market expansion until 2027 [29].

North America emerged as the leading region in 2019, with a market value of USD 10.65 billion. It is expected to continue to dominate the market share in future years. The rapid growth of chronic diseases such as diabetes in the United States is driven by increased awareness and continued R&D in improved devices, in conjunction with new product launches, which are the key causes responsible for North America's supremacy. Europe has the second-largest market share. The rising prevalence of chronic diseases and the presence of a substantial target population base are driving up product demand in the region. This, together with large pharmaceutical businesses in countries such as Ireland, Italy, and Switzerland, is expected to accelerate market expansion [29].

3.3. Neurovascular Catheters

Neurovascular catheters are used to perform procedures in the brain and intracranial regions. Catheters used for these operations are specially developed because neurovascular tissue is extremely sensitive, and catheter failure or malfunction might result in vessel injury and perforation. These catheters are used for various purposes, including access to the neurovasculature and introducing embolic coils and thrombectomy devices [30].

3.3.1. Instrumentation

There are 4 main types of neurovascular catheters and they are as follows:

1. Embolization catheter
2. Mechanical thrombectomy catheter
3. Microcatheter
4. Balloon catheter

Embolization catheter: Catheter embolization injects drugs or synthetic materials known as embolic agents through a catheter into a blood vessel to limit blood flow to a specific part of the body. It can be used to cure aneurysms, control or avoid abnormal bleeding, block off vessels feeding blood to a tumor, delete aberrant connections between arteries and veins, or control or prevent abnormal bleeding. Embolization is a highly successful method of bleeding management that is far less intrusive than open surgery [34].
The interventional radiologist inserts a catheter through the skin into an artery and advances it to the treatment location using X-ray imaging and a contrast substance to see the blood vessel. An embolic agent, a synthetic material or drug, is introduced through the catheter and permanently positioned into the blood vessel or abnormality [34]. Similar procedures are followed for the rest of the catheters.

Mechanical thrombectomy catheter: A *thrombectomy* is a minimally invasive endovascular procedure designed to remove blood clots from an artery or vein in order to restore blood flow. It may be used to treat deep vein thrombosis (DVT), acute mesenteric ischemia, renal artery occlusion, myocardial infarction, pulmonary embolism, and stroke. The surgeon inserts a catheter into the blood vessel proximal to the clot. Continuous imaging scans are necessary to guide the catheter and specific devices through the patient's blood vessels to the area of the blood clot [80]. Special instruments are used to break up the clot, dissolve it, or suction it out.

Microcatheter: Microcatheters are small 0.70-1.30mm diameter catheters used in complex endovascular operations for guidewire support, exchanges, accessing distal anatomy, crossing lesions, delivering therapeutic emboli, injecting contrast media, and performing other procedures (Figure 13). The catheter has been engineered to resist kinking concerning the proximal and distal ends of the structure [31].

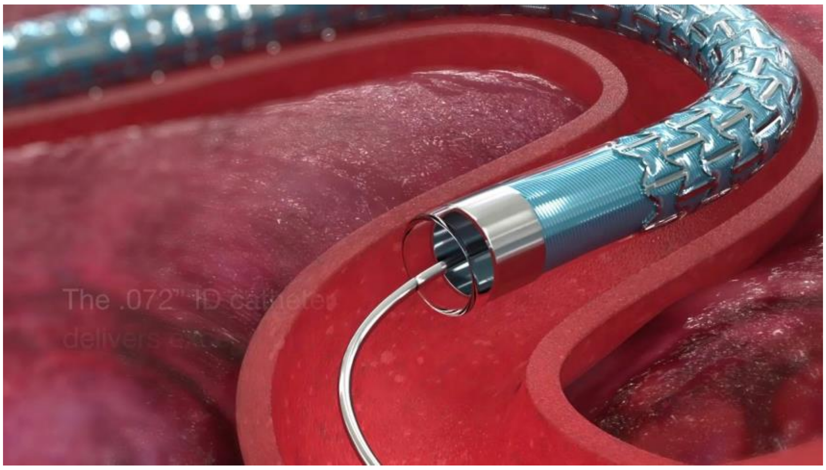

Figure 13. Neurovascular catheter (29).

3.3.2. Market

The global neurovascular catheter market was worth USD 625.6 million in 2018. It is expected to be worth USD 1,083.5 million by 2026, at a CAGR of 7.1%. Thrombectomy catheters account for 44.3% market share [30]. With the advantages of minimally invasive surgery (see section 3.1.2), advanced neurovascular catheters have been developed for various applications. Due to advances in catheter design, certain advantages offered by these catheters during the next few years will boost their adoption and drive neurovascular catheter market trends, including minimal invasion, easy access to intracranial spaces, and simplifying complex processes.

The increasing adoption of neurovascular catheters is firstly due to the rising prevalence of strokes. According to the Global Stroke Fact Sheet (2022) compiled by the World Stroke Organization (WSO), there are currently over 101 million people living in the world who have had a stroke. Every year, nearly 12.2 million new strokes occur. One in four adults over 25 will suffer a stroke throughout their lifetime [62].

According to the World Stroke Organization's (WSO) Global Stroke Fact Sheet (2022), Ischemic strokes account for more than 62% of all incident strokes worldwide. About 77 million people live in the world who have had an ischemic stroke. Every year, nearly 7.6 million incidents of ischemic stroke occur [62]. Due to the prevalence of ischemic strokes, there is significant demand for thrombectomy catheters because of their effectiveness in treating this kind of stroke. In addition, it can potentially reduce long-term disability caused by a stroke. This explains the large market share thrombectomy catheters occupy.

Increased patient awareness of treatment availability, equipment, and payment system realignment, particularly in emerging nations, will likely boost market demand even further. Moreover, introducing novel catheters with ergonomic designs and improved clinical efficiency increases the global adoption of these devices in neurovascular procedures.

The neurovascular catheters market structure is semi-consolidated, with key players such as Stryker, Medtronic, and Penumbra, Inc. holding a leading position. The dominance of these businesses in the global market is mainly owed to their solid and diverse portfolios and a broad distribution network. Microvention Inc., Zeus Industrial Products, Inc., Biomerics, Teleflex Incorporated, and Integra LifeSciences Corporation are other participants in the neurovascular catheter industry [30].

3.3.3. Further remarks

In 2018, the North American neurovascular catheter market was worth USD 271.6 million. This region's dominance is linked to reasonable reimbursement regulations and an increase in neurovascular illnesses, resulting in great demand for catheters. According to the CDC, approximately 795,000 people in the United States suffer from a stroke each year [81]. Such figures are predicted to increase market growth in North America by the end of 2026. The market in Europe is expected to grow during this period. This is due to rising awareness of neurovascular problems, an emphasis on minimally invasive operations, and the widespread use of sophisticated catheters [30]. During the projected period, the Asia-Pacific market is expected to develop faster. Certain variables contributing to this rise include the increasing prevalence of neurovascular illnesses in this region, such as ischemia, brain aneurysms, and arteriovenous malformations. Similarly, Latin America, the Middle East, and Africa are predicted to grow at a moderate CAGR during the forecast period. This is because healthcare infrastructure develops and the frequency of neurovascular diseases rises [30]. From 2018 to 2026, the microcatheter sector is expected to grow at a faster rate. The introduction of novel catheters by market players and an increase in the number of patients undergoing neurovascular procedures, combined with the clinical benefits of microcatheters, are projected to drive demand for these catheters [30].

Despite an increasing global incidence of strokes and hemorrhages and a vast patient pool with neurovascular illnesses, several limitations restrict the adoption of neurovascular catheters. The low treatment rate for neurovascular illnesses in emerging countries is one of the primary factors inhibiting market growth. This is due to the high operations cost and a need for appropriate reimbursement rules [30]. This reduces the number of patients receiving treatment and adopting catheter devices in these nations.

3.4. Surgical Instruments in Neurosurgery

According to SurgicalHoldings, a surgical instrument is a specially engineered tool used to execute particular tasks or achieve specified effects during an operation. This includes altering biological tissue or providing access to or viewing it [73]. Scalpels, tweezers, forceps, surgical knives, and other inventive devices made of bronze, iron, and silver were made by surgeons in Greece and Rome in the ancient world. Various instruments were devised and designed in the Renaissance and post-Renaissance eras to accompany the greater boldness of surgeons. Due to the increased severity of war-inflicted wounds from shots, bullets, and cannons, amputation sets were developed at this time [74].

Novel surgical instruments were produced when anesthesia and medical asepsis were discovered. This allowed entry into the inner sanctum, or hitherto restricted body cavities, such as the skull, thorax, and abdomen. Hundreds of novel surgical procedures were invented throughout the nineteenth century and the first decades of the twentieth century, resulting in a remarkable explosion of new equipment. New materials such as stainless steel, chromium, titanium, and vanadium became available to manufacture these instruments. Precision instruments for microsurgery in neurosurgery, ophthalmology, and otology were possible. Power-based instruments, such as electrocauteries, ultrasound, electric scalpels, and tools for endoscopic surgery and surgery robots, were first developed in the second half of the twentieth century [35].

3.4.1. Instrumentation

There is no universal standard for how surgical instruments are categorized. Hence, a logical way to categorize them is through their performing action (i.e., cutting, grasping) as done by Surtex Instruments.

Cutting and Dissecting: Many surgical instruments are used to cut skin, soft tissue, and even bones, as well as to dissect tissues along anatomical planes. Some of this equipment, such as scalpels and blades, are disposable, while others, such as knives, are reusable. Different-sized blades are used for different applications [38].

Grasping and Handling: Surgeons use surgical instruments to grasp or hold tissues to better view of their operating field. Forceps (including tissue forceps, smoothing forceps, toothed forceps, Allis forceps, Babcock forceps, and stone forceps), tenaculum, and bone holds are the most common surgical devices used for this purpose [38].

Clamping and Occluding: These instruments are often used during surgery to clamp blood vessels or other tissue to remove them from the field. Hemostatic forceps, hemostats, crushing clamps, and non-crushing vascular cramps are some of them [38].

Retracting and Exposing: Retractors allow surgeons to see the operative field more clearly. Surgeons use those devices to pull tissues without injuring them. Self-retaining retractors like the GELPI perineal retractor allow for easier visualization [38]. In 1968, Turkish neurosurgeon Mahmut Gazi Yaşargil created the Leyla retractor, a flexible self-retaining retractor that was initially affixed to the edge of the craniotomy [82].

Suturing and Stapling: Instruments for suturing and stapling are used to bring the borders of skin and soft tissue adjacent together. Suturing material, a needle, a needle holder, toothed forceps, and a Cine suturing scissor are all included in a conventional suturing kit. Tungsten carbide jaws are used to prevent needle spinning and twisting, extend the instrument's life and improve grip and balance [38].

Suctioning and Aspiration: Blood and large fluid volumes can flood surgical and dental procedures, obscuring the underlying tissues. Consequently, surgeons need specific equipment to remove these fluids from their fields, such as the Frazier tip, which is used in brain and orthopedic procedures [38].

Visualization: Surgeons employ imaging technology such as magnetic resonance imaging (MRI), intraoperative MRI, computed tomography (CT), and positron emission tomography (PET) scans to generate a 3D model of the patient's brain in computer-assisted brain surgery. This can be done before or during surgery in some situations [83]. In addition to these imaging modalities, neuro endoscopes look inside the brain's ventricles. See section 3.1 for more details on neurosurgery endoscopes.

Other types of surgical instruments used in neurosurgery are powered instruments— a craniotomy drill, for instance. The instruments are similar to those previously mentioned. However, they perform a cutting or drilling action much more quickly. This allows surgeons to perform surgery at full tilt and limits the duration of open wounds in the operating room.

3.4.2. Market

The surgical instrument market is expected to reach $28.3 billion by 2026, increasing at an annual rate of 8.0 percent from 2021 to 2026 [36]. Since surgical tools are essential to perform

any neurosurgery, the market is driven by the rising prevalence of neurological diseases requiring neurosurgery. According to the WHO, in 2019, stroke accounted for 11% of deaths, making it the second largest cause of death [66]. Therefore, the increasing prevalence of strokes is a crucial neurological disease driving the neurosurgical instrument market.

According to the United Nations [67], in 2020, there will be 727 million people aged 65 and up globally. This figure is expected to more than double by 2050, reaching more than 1.5 billion people. The proportion of older adults worldwide is anticipated to rise from 9.3% in 2020 to 16.0% in 2050. Older people are more prone to chronic ailments, which may increase demand for various surgical procedures, hence increasing demand for surgical equipment and other medical devices. According to the WHO road traffic injuries factsheet [68], around 1.3 million people die yearly from traffic accidents. These accidents cost most nations 3% of their GDP. Non-fatal injuries affect between 20 and 50 million more people, with many becoming disabled due to their injuries. The introduction of advanced technological instruments and MIS instruments aids in new and current minimally invasive neurosurgical treatments and hence is another factor that contributes to market growth. Medtronic plc, Progressive Medical, Inc., Scanlan International, Abbott Laboratories Inc., Boston Scientific Corporation, HOYA Corporation, Koninklijke Philips N.V., Biolitec AG, Stryker Corporation, and Johnson & Johnson are among the top ten firms in the general Surgical Instruments Market [36].

3.4.3. Further remarks

The surgical instruments market is well-established. Hence, having existed for a long time leads to a saturated market. In 2019, North America dominated the operative equipment market with a 28.9% share. This is due to increased healthcare spending in the United States, which has resulted in well-established hospital infrastructures and the availability of highly qualified surgeons. According to the 2018 World Integrated Trade Solution report, Europe is one of the world's leading suppliers of medical and surgical instruments. The Netherlands, Germany, and Belgium are just a handful of major regional markets with promising growth prospects [37].

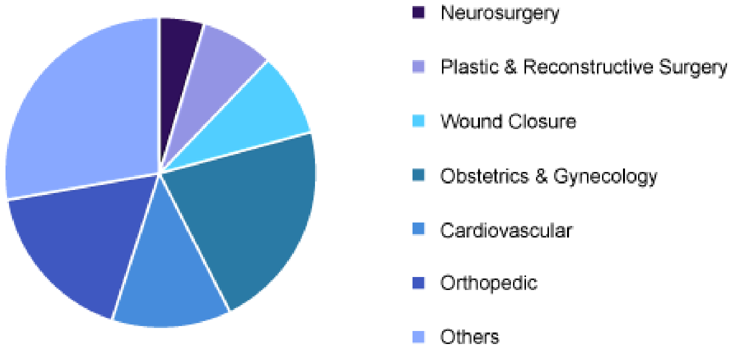

Figure 14 Global surgical equipment market share, by application, 2020 (%) [36]

From Figure 14, we can see that surgical instruments in neurosurgery, account for approximately 4.7% of the overall surgical instruments market. Hence, if we concentrate on surgical instruments in neurosurgery the CAGR will go down significantly to 0.376% according to the market share it occupies in surgical instruments.

3.5. Invasive Neurostimulation

Neurostimulation is the intentional modification of nervous system activity through invasive (e.g., microelectrodes) or non-invasive methods (e.g., transcranial magnetic stimulation or transcranial electric stimulation, tES, such as tDCS or transcranial alternating current stimulation, tACS). Electromagnetic methods used for neuromodulation are commonly referred to as neurostimulation [40]. A neurostimulation device is a medical transmitter that can send electrical signals to particular brain areas. The device can stimulate, inhibit, modify, control, and change the activity of the patient's autonomous, central, and peripheral nervous systems. This primarily treats various medical conditions, including movement problems, chronic pain, Parkinson’s disease, and epilepsy.

Neurostimulation technology can help those severely paralyzed or with substantial losses to multiple sensory organs and those who suffer from severe, chronic pain that would otherwise necessitate constant (round-the-clock) high-dose opioid medication (such as neuropathic pain and spinal cord injury). It is used in hearing aids, artificial vision, artificial limbs, and brain-machine interfaces, among other things [40].

The Human Brain Project Innovation Team has drafted a global view of the current and future evolution of neurostimulation technologies and the associated market with an eye on the possible interaction with the results of the HBP and EBRAINS services in a complete report titled "Neurostimulation Devices and its Role in the Industrial Health Sector" [75].

3.5.1. Instrumentation

Neurostimulation can be categorized into invasive and non-invasive. This report focuses on invasive neurostimulation as it is one of the focus of the top ten neurosurgery companies in addition to invasive neurosurgery. The products offered by these companies are related to deep brain stimulation, spinal cord stimulation, and dorsal root ganglion stimulation. Other prominent types of neurostimulation are sacral nerve stimulation and vagus nerve stimulation.

Deep Brain Stimulation (DBS): A neurosurgical operation that employs electrical stimulation and implanted electrodes to treat movement disorders such as Parkinson's disease (PD), essential tremors, dystonia, and other neurological illnesses. Disorganized electrical signals in the parts of the brain that govern movement generate movement-related symptoms in Parkinson's disease and other neurological diseases. When successful, DBS is thought to suppress abnormal circuit oscillations associated with tremors and and other movement disorders [48]. Neurosurgeons implant one or more leads inside the brain after a battery of tests to find the most suitable location. The leads are connected to a neurostimulator (electrical generator) placed beneath the person's collarbone by an insulated wire extension. The neurostimulator sends continuous pulses of electric current through the leads and into the brain.

Vagus Nerve Stimulation (VNS): The employment of a device to stimulate the vagus nerve with electrical impulses is known as vagus nerve stimulation. The device is surgically placed under the skin on the chest. In traditional vagus nerve stimulation, a wire is placed under the skin to attach the device to the left vagus nerve. When the device is turned on, it transmits electrical signals to the brainstem, which sends messages to specific brain sections. The FDA has approved an implanted vagus nerve stimulator to treat epilepsy and depression [45].

Spinal Cord Stimulation (SCS): Spinal cord stimulators comprise thin wires (electrodes) and a compact battery pack that looks like a pacemaker (the generator). The electrodes are placed between the spinal cord and the vertebrae in the epidural space. The generator is placed beneath the skin, usually towards the buttocks or abdomen. Patients using spinal cord stimulators can use a remote control to emit electrical impulses when in pain [47].

Sacral Nerve Stimulation (SNS): The sacral area is the primary channel that runs from the brain via the spinal cord and the lower back. Nerve routes diverge here and branch off in many directions, some leading to the pelvic area. The brain controls the muscles in the pelvic area, such as the abdominal floor, urethral sphincters, bladder, and anal sphincter muscles, via nerves that travel from the sacral area. These nerve channels also carry experiences, such as fullness in the bladder or rectum, to the brain [46]. Sacral neuromodulation helps modify information delivered along these neural pathways that are inappropriate, undesirable, or incorrect.

Dorsal Root Ganglion (DRG) Stimulation: DRG stimulation therapy is a new neurostimulation therapy meant to relieve chronic pain in difficult-to-treat lower body parts, such as the foot, knee, hip, or groin [49]. The dorsal root ganglia (DRG) is stimulated during DRG stimulation therapy (DRGs), which regulate impulses and sensations that travel through nerve fibers to the brain. In this way, DRG therapy has the unique capacity to manage pain in specific sections of the body effectively. This is especially beneficial for patients who suffer from isolated chronic pain in the lower body [49].

3.5.2. Market

The global neurostimulation devices market was worth USD 5.21 billion in 2020. It is expected to increase at a CAGR of 11.76 percent from 2021 to 2026, reaching USD 11.28 billion [41]. Another market research firm, IMARC Group, estimates a CAGR of 11.8% [42]. In addition, they indicated that the global neurostimulation devices market was worth USD 6.3 billion in 2020, a difference of USD 1.1 billion from DelveInsight.

The main factors increasing the demand for neurostimulation systems are the growing incidence of chronic diseases, such as migraine, Parkinson’s disease, dystonia, and epilepsy increasing product demand as add-on therapy, rise in prevalence of lifestyle diseases such as depression and chronic pain, adoption of technologically advanced products, and rising elderly population [41]. For example, the prevalence of Parkinson's disease has more than doubled in the last 25 years. According to 2019 estimates, approximately 8.5 million people worldwide have Parkinson's disease. According to current estimates, PD caused 5.8 million disability- adjusted life years (DALYs) in 2019, an increase of 81% since 2000, and 329 000 deaths, an increase of more than 100% since 2000 [56].

Regarding chronic pain, Boston University found that CP affects approximately 20% of individuals globally, with prevalence increasing with age [69].

Depression is a widespread mental illness, and it is believed that 5% of adults worldwide suffer from depression [57]. According to the Institute for Health Metrics and Evaluation (IHME), epilepsy prevalence reached 0.34% and migraine 15.16% in the global population in 2019 [57]. All of these diseases can be aided or treated with neurostimulation devices. Therefore, the increasing prevalence of such diseases will increase the demand for these devices.

As discussed in section 3.4.2 above, the growing elderly population will increase the demand for numerous medical devices, including neurostimulation systems. In addition, many neurologic illnesses, particularly neurodegenerative disorders, become more common as people age.

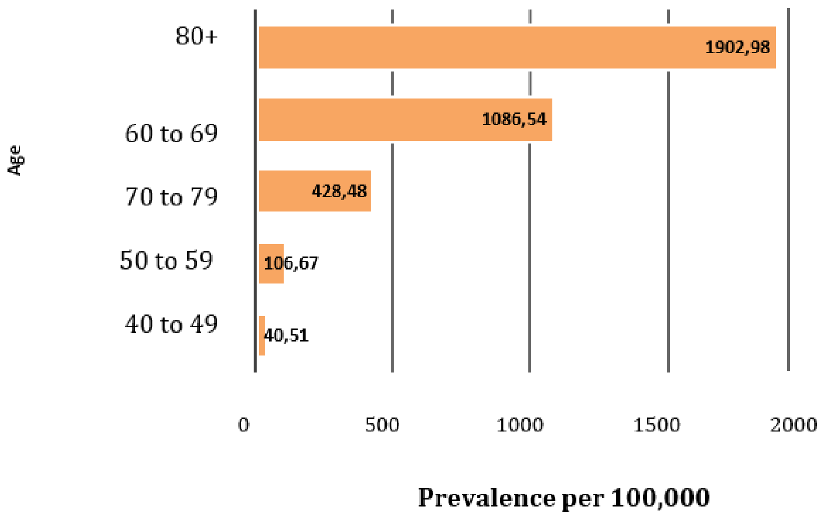

Figure 15. Global prevalence of neurological illnesses in 40+ year old [55].

Figure 15 demonstrates that the meta-analysis of global data found a prevalence of 40.51 per 100,000 in people aged 40 to 49, 106.67 per 100,000 in people aged 50 to 59, 428.48 per 100,000 in people aged 60 to 69, 1,086.54 per 100,000 in people aged 70 to 79, and 1,902.98 per 100,000 in people aged 80 and up [55]. These statistics considered Multiple sclerosis, Parkinson's disease, epilepsy, Huntington's disease, spinal cord injury, Duchene muscular dystrophy, cervical dystonia, brain tumors, Spina bifida, hydrocephalus, traumatic brain injury, cerebral palsy, Tourette syndrome, and dementia. Therefore, the incidence of these chronic neurological illnesses increases with age, and as discussed earlier in sections 3.2.2 and 3.4.2, the aging population is rising rapidly. Therefore, chronic disease and age are two major factors positively impacting the neurostimulation devices market.

In addition to the growing prevalence of neurological diseases, Allied Market Research also argues that the increase in R&D investments by several major pharmaceutical companies will contribute to the growth of the global neurostimulation devices market [43]. Abbott Laboratories, Aleva Neurotherapeutics SA, ElectroCore Inc., EndoStim Inc., Biocontrol Medical, Boston Scientific Corporation, Cyberonics Inc., Medtronic Inc., Neuronetics Inc., Neuropace Inc., Neurosigma Inc., Nevro Corporation, ST. Jude Medical Inc., and Synapse Biomedical Inc. are some of the key players in the industry [22, 23].

3.5.3. Further remarks

The neurostimulation market is an excellent market to pursue due to its acceptable CAGR and capacity for innovation. The neurostimulation market is well established, as the first neurostimulator was made in the early 1960s, and it was a DBS system. Shortly after, the SCS system was introduced in 1967 [44]. The four main types of neurostimulation devices are DBS, SCS, VNS, and SNS.

The spinal cord stimulators component is the most profitable in the global neurostimulation market. This is due to an increase in the use of spinal cord stimulators for treating neuropathic pain and spine injuries, an increase in minimally invasive procedures, and an increase in healthcare spending driving global market growth for spinal cord stimulators. The market is expected to grow at a significant CAGR due to the use of DBS in various diseases such as Parkinson's disease, obsessive-compulsive disorders, idiopathic dystonia, and essential tremor, as well as an increase in the number of product approvals [43].

3.6. Neurosurgical Robotics devices

Robots are programmable machines that can perform autonomous or controlled tasks. On a basic level, all robots will include some actuator, sensor, and control system. Like biological muscles, actuators are devices and subsystems within a robot that generate forces and motion. Sensors, like our sensory nervous system, allow robotic systems to sense themselves and their surroundings. Controllers function similarly to brains in acquiring and processing sensory input information and output commands to the actuation system. These individual components are assembled and organized to form an integrated robot.

Robotic neurosurgery is a rapidly evolving technology that offers several advantages over traditional neurological surgery, including improved outcomes, enhanced accuracy, faster recovery, and a shorter hospital stay [52]. In addition, they offer reduced post-surgery pain and discomfort, decreased blood loss, and fewer and smaller scars resulting in a reduced risk of infection.

Neurosurgeons offer better dexterity, excellent vision, and improved precision. The Animation PUMA (Programmable Universal Machine for Assembly) 200 robot, designed for industrial use, was used to precisely position a needle using CT guidance during a stereotactic biopsy of a deep intracerebral lesion in a 52-year-old male. Although needle advancement and biopsy were performed by hand, the ability of a robot to precisely position the biopsy needle was a technological first. This was quickly followed by using the same robot (PUMA 200) to assist with the surgical resection of low-grade thalamic tumors in children.

The NeuroMate robot was the first FDA-approved robotic device explicitly designed for neurosurgical use (Integrated Surgical Systems, Sacramento, California, US). Several robotic devices are available for the spinal surgery that provide tool guidance and implant placement confirmation. [51] An excellent example of this in modern robotics is the Neuralink robotic system, with its paramount precision and speed. The threads (1024 electrodes) on the Link (BCI) are so thin (20x thinner than a human hair) and flexible that they cannot be implanted by the human hand [71]. The Rosa One Brain is a more flexible example of a neurosurgery general application. It is a minimally-invasive robotic platform designed for stereotactic neurosurgery to assist surgeons in planning and performing difficult neurosurgery procedures [76].

Even though there are numerous robotic systems on the showcase for application in neurosurgery, they can all be broadly classified into rigid robotic systems and continuum robotics.

3.6.1. Instrumentation

This section is based on the technical background of the HBP Innovation Team. It heavily relies on the expertise of the book "Neurosurgical Robotics" [50] due to its high technical level and focuses on neurosurgical robotics precisely. Thus, this section is highly technical and all information is factual, this book was more than enough to complete it. The most frequent robot architectures used in medical applications are based on traditional robotic manipulator designs resembling a human arm. Robot arms, like human arms, are made up of links connected by joints that can rotate (revolute joints) and, in some circumstances, translate (prismatic joints). This chain of links and joints usually refers to the base in the robot being anchored. The robot arm can make articulated movements relative to the base thanks to these joints' coordinated rotation and translation [50].

The end-effector is the most distal part of a robot arm; an industrial robot could be a robotic hand or welding instrument; a medical robot could be an interventional tool or imaging equipment. These basic features of a robotic manipulator are depicted in Figure 16. The number of degrees of freedom (DoF) robotic manipulators possess is another feature of interest. In robotics, a degree of freedom refers to a robot's ability to move independently. The degree of freedom (DoFs) a robot has determined how far the robot arm can move in space [50].

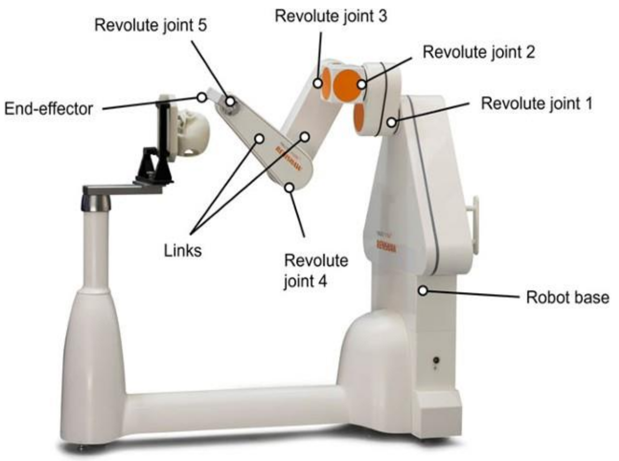

Figure 16. Basic features of a rigid robotic system, as shown on the Renishaw Neuromate® [50].

A robot's reachable workspace is a volume that specifies the entire physical region that the robot's end-effector can access. The dexterous workspace, which characterizes the actual volume in which the robot can move with each DoF such that the end-effector can be positioned and oriented arbitrarily, is of higher interest [50]. The rigid robotic systems mentioned so far can be divided into serial and parallel architectures.

Serial robots are designed with each connection and joint organized sequentially like human arms. These robots can provide a vast dexterous workspace, allowing them to reach long distances and in various directions [50].

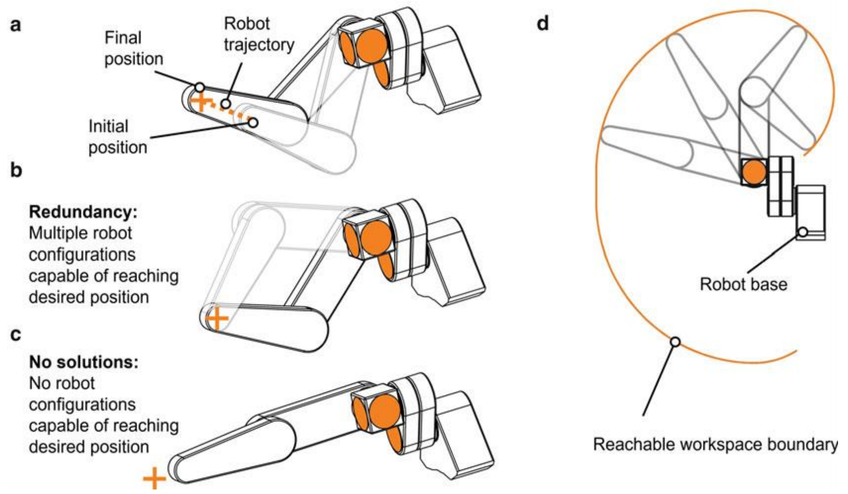

Figure 17. (a) Illustration of a robot moving through a trajectory from an initial position to a new position. (b) Illustration of redundancy in a robotic system in which multiple kinematic configurations of the robotic system can reach the same point. (c) Example of when no kinematic configurations exist for a robot commanded to reach a position beyond its workspace. (d) Illustrative example of the outer boundary limit of the reachable workspace for a robotic manipulator [50].

Parallel robotic designs provide advantages over serial robotic architectures, such as higher positioning accuracy and faster acceleration. Even though robots can move with extreme precision, no robotic joint is Clawless, and there will always be some positioning errors. In a serial design, errors in the location of each joint accrue down the chain of links and joints, eventually resulting in a significant mistake at the end-effector position. Parallel robots, conversely, can be constructed with fewer links in each chain, and any mistakes that occur are averaged across the robot. Compared to a single linkage chain, the parallel linkage architecture of these robots is innately stiffer, and this excellent mechanical stability also helps reduce positioning mistakes. Parallel robots have the disadvantage that their geometrical configuration fundamentally confines their workspace, as the separate linkage chains in a parallel robot may collide.

The target application frequently determines the robot structure. The NeuroArm robotic system (University of Calgary), for example, uses serial manipulators, but the SpineAssist® device (Medtronic plc, Minneapolis, USA) has a similar design (see Figure 17). The NeuroArm device is intended to do immediate surgery on a patient like a surgeon. The surgeon uses a user interface to control a robotic manipulator that reads their input motions and recreates them. An anthropomorphic robotic arm based on serial architecture is a better fit for this application since its basic structure is similar to the human arm it emulates. Furthermore, the end-effector placement of this serial robot chain can provide a vast workspace, allowing for dexterous articulation of the interventional tool at the surgical site.

A parallel robot architecture is an appropriate design choice for the SpineAssist® robot, which is built for image-guided needle placement when positional precision is a significant design input need [50].

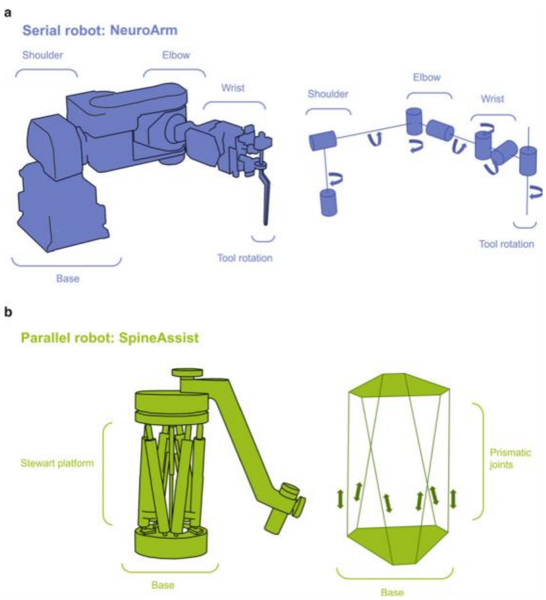

Figure 18. The NeuroArm system is an example of serial robot design, while the SpineAssist® device (Medtronic plc, Minneapolis, USA) is an example of parallel robot architecture [50]

Rigid robotic manipulators have been widely used in manufacturing applications due to their intrinsic rigidity, allowing for precise and repeatable positioning. This same quality is helpful in neurosurgery; the NeuroArm and SpineAssist® systems (portrayed in Figure 18) use rigid manipulators to achieve good positioning precision. Nevertheless, rigid robotic designs have inherent limitations that can be troublesome in surgical settings. Their stiff form makes them potentially dangerous for direct patient interaction, as a collision could result in serious injury [50].

Second, while rigid robots effectively position instruments outside the body, miniaturizing articulated robot designs to the physical scales required for endoscopic procedures is technically complex and often unfeasible. Continuum robot designs, which achieve dexterity through physical deformation, offer an alternative to rigid robotic systems [50]. These tentacle- like appendages' smooth, continuous motions make them perfect for negotiating limited regions and challenging courses within the body.

Continuum robotic systems can look like catheters, with tendons deflecting a flexible tooltip. Multiple tendons that can each be separately manipulated to generate complicated, coordinated snake-like motions can be incorporated into highly dexterous continuous robotics. These designs, like traditional flexible endoscopes, can include cameras, light sources, and passageways for interventional instruments, as portrayed in Figure 19. Other concepts use snake-like manipulators with actable flexible backbones. Concentric tube robots can do similar dexterous manipulation feats. These systems comprise nested tubes made of a highly elastic material like Nitinol and have some degree of predefined curvature. Individual nested tubes can be independently translated and rotated by a robotic control system, resulting in the complete tubular assembly's coordinated deflection and snaking motions. Interventional instrumentation can be passed through the entire tube assembly to enable complicated robotic systems because these robots are tubular. Another type of continuous robot helpful to neurosurgery is needle steering robotic systems. Most interventional needles are rigid and engineered to stay straight when put into soft tissue [50].

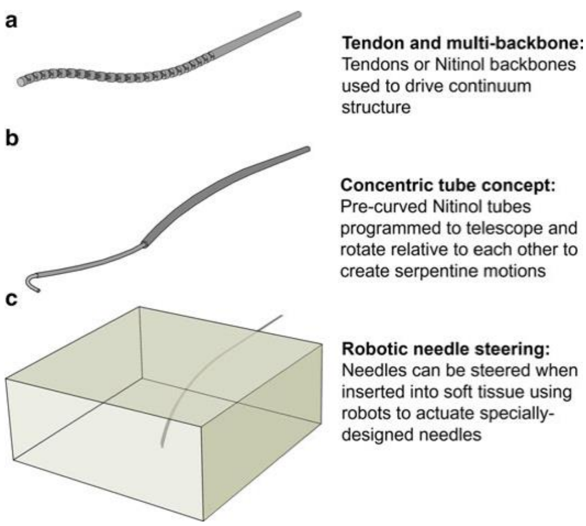

Figure 19. Examples of continuum-based robotic architectures [50].

Robotics researchers build flexible needles to deflect predictably when placed into soft tissue, allowing the needle insertion trajectory to be preplanned. This method can allow for precise needle placement in a specific brain region while avoiding important structures in neurosurgery.

Finally, UI paradigms are divided into three types for surgical robotics: supervisory control, remote operation, and shared control. **Supervisory control**

robotic systems are primarily automated systems that resemble traditional industrial robots in appearance. In order to undertake a surgical intervention, a supervisory-control robot is preprogrammed to complete a specified set of activities. Because supervisory-control robots cannot undertake adjustments during an intervention, such systems necessitate extensive preoperative planning for the robot to fulfil its tasks efficiently. This robot paradigm frequently employs preoperative medical imaging and image guidance technologies. A robotic manipulator can plan how to perform an intervention by co-registering 3D medical imaging data with the patient. Because a robotic manipulator may substantially improve positional precision, needle placement techniques, and radiotherapy are typical applications for supervisory-control systems. Because co-registration of the cranial and spinal anatomy can be done correctly as these structures are relatively rigid, this robot has seen much application in brain and spine operations [50].

Teleoperated robotic systems allow a surgeon to manage an interventional robotic device in real-time while operating from a distance. The surgeon usually sits at a console with a view of the operative scene. The surgeon can change connection mechanisms that track the surgeon's input movements at the console. A computer control system then processes these motions before being duplicated on a robot that performs the procedure on the patient [50]. This user-interface technique can be helpful since the robot system can work with high precision, yet the surgeon always retains executive control [50]. In the broader field of medical robotics, the teleoperated robotic system paradigm has received significant clinical adoption; notably, the da Vinci® robot (Intuitive Surgical, Sunnyvale, CA, USA) has been heavily accepted in various clinical applications. Teleoperated systems could thus help do keyhole neurosurgical operations that would otherwise be difficult to perform manually. Teleoperated systems can also help surgeons execute procedures in physically demanding situations. The NeuroArm system, for example, has the advantage of performing surgery near an MRI scanner, allowing a surgeon to intervene and rescan a patient to ensure complete tumor removal [50]. Because interventional robotic equipment may be shrunk and their motion scaled down, teleoperated robots can also benefit surgeons by allowing them to operate on lower physical scales [50].

Shared control robots are designed to allow a surgeon to maintain executive control while controlling the robotic platform in real-time. Unlike teleoperated devices, a shared control robot can be controlled directly by the operating surgeon rather than through a remote panel. By eliminating the need for a remote console and its gear, the complexity of the operating robot is reduced.

Shared-control robots, like teleoperated systems, combine the advantages of people and robotics. Shared-control systems enable interventions to be performed with superhuman precision or delicacy while the surgeon retains high-level judgment and decision-making authority. Robotic features can be integrated into ungrounded handheld devices, or shared-control robots can be tethered to the ground like a traditional robotic manipulator [50]. These "smart" handheld equipment provides some benefits of more giant robots at a cheaper cost and with the possibility for seamless integration into the surgical workflow. As a result, different robot architectures coupled with an appropriate user interface will produce a robot with relevant features ideal for its purpose. This is whether the robot is created for needle positioning, dexterous articulation of the interventional tool at the surgical site, or a collection of tasks.

3.6.2. Market

By 2027, the Global neurosurgical robot market will have grown by 16.8% yearly to $2,010.7 million. Furthermore, the European neurosurgery robots' market was worth $165.6 million in 2020 and is expected to expand 16.5 percent per year from 2020 to 2027 [52, 53].

The aging population is essential for market growth in numerous neurosurgery areas, including neurosurgical robotics. This is because neurosurgical robotics is among the advanced tools used to treat chronic illnesses that require surgery. Older people are more prone to these chronic ailments, which may increase the demand for various surgical procedures and enlarge the demand for surgical robotics. See sections 3.2.2 & 3.4.2 for more details. Undeniably, the incidence of neurological diseases that require surgery is another important factor that will increase the demand for neurosurgical robotics. See sections 3.2.2, 3.3.2, 3.4.2, and 3.5.2 for more details.

The improved benefits of robotics-based procedures (see section 3.6), the decreasing price of robot- assisted neurology surgery, and the increase in the purchasing power of hospitals are all specific factors driving its global market. The shortage of skilled workers is projected to stifle market expansion [52]. According to Dr. Julio Mayol, president of the Spanish Society for Surgical Research, "Robots can help us reduce the variability of practice and increase the safety of surgery. Their price is indeed high, but that is going to change. There will likely be more competition when Da Vinci's patents end. [70]. Therefore, the current price of neurosurgical robotics as well as the scarcity of skilled workers, are two factors that may negatively impact the market at this time. Nevertheless, due to their advantages over traditional surgeries, innovation potential, surgical application reach, compatibility with all age groups, and surgical precision, the market is expected to snowball, exceeding the CAGR of other neurosurgery areas.

3.6.3. Further remarks

The neurostimulation market is an excellent market to pursue due to its acceptable CAGR and capacity for innovation. The neurostimulation market is well established, as the first neurostimulator was made in the early 1960s, and it was a DBS system. Shortly after, the SCS system was was introduced in 1967 [44]. The four main types of neurostimulation devices are DBS, SCS, VNS, and SNS. The spinal cord stimulators segment is the most profitable in the global neurostimulation market. This is due to an increased use of spinal cord stimulators for treating neuropathic pain and spine injuries, an increase in minimally invasive procedures, and an increase in healthcare spending driving global market growth for spinal cord stimulators. The market is expected to grow at a significant CAGR due to the use of DBS in various diseases such as Parkinson's disease, obsessive-compulsive disorders, idiopathic dystonia, and essential tremor, as well as an increase in the number of product approvals [43].

4. Conclusion

The analysis carried out through the analysis of the Quadruple Helix model allows for a comprehensive understanding of the market and its stakeholders, including academia, policymakers, industry, and civil society. Furthermore, by analyzing the interactions and collaborations between these stakeholders, we have identified areas where innovation and progress can be facilitated and address any potential challenges or barriers.

Industry is the driving force behind the neurosurgery technology market, providing the necessary investment, resources, and expertise to bring innovative solutions to the market. Industry partners collaborate with academia and policy stakeholders to develop and commercialize neurosurgical robotics, driving market growth and addressing the neurosurgery industry’s challenges. The report lists the top ten global medical device companies that excel in neurosurgery devices, which is vital for understanding the competitive landscape in this market. Upon analysis of said table, we drew the conclusion that the majority of these companies are based in the United States (4 out of 10) and Europe (3 out of 10), followed by Japan (2 out of 10) and Australia (1 out of 10). In terms of field of expertise, it can be observed that most of these companies (7 out of 10) specialize in neurostimulation devices, such as deep brain stimulation systems and spinal cord stimulation systems. The remaining three companies specialize in neurosurgical navigation systems, endoscopic systems, and brain monitoring systems, respectively. The fact that the majority of the companies in the top 10 are based in developed countries with well-established innovation ecosystems and strong support for research and development suggests that there may be a correlation between a country's innovation capacity and the success of its medical device companies. This could indicate that countries with strong innovation ecosystems and support for R&D may be better positioned to drive innovation and technological development in the neurosurgery technology market.

Policy also plays an essential role in shaping the neurosurgery technology market. The regulatory bodies responsible for approving neurosurgery devices and technologies ensure patient safety and efficacy, which can boost consumer coincidence and adoption. A favorable regulatory environment encourages industry investment in research and development, while an unfavorable regulatory environment may stifle innovation and limit industry growth. In this sense, the research in this report suggests that regulatory factors, such as the FDA's approval process in the United States, have created barriers to entry for new players in the market. The statement highlights the significant role of policy and regulatory bodies in shaping the neurosurgery technology market, since the regulatory environment determines the level of investment in research and development, industry growth, and consumer coincidence and adoption.

Together with industry and policy, academia is critical in advancing neurosurgery technology and robotic-assisted surgery. Research and development of these technologies are primarily conducted by academic institutions (a list of the most prominent institutions was provided under section 2.2.2 of this report). In collaboration with industry partners, academic institutions can create innovative solutions to address neurosurgery's current challenges and limitations. The academia-industry partnership is essential in developing neurosurgical robotics, as it provides a platform for knowledge exchange, technological transfer, and commercialization. Thus, establishing collaborations between academia and industry can be a crucial driver of innovation. This can be achieved through joint research projects, sharing of resources, and personnel exchanges. Moreover, creating funding mechanisms (such as grants or subsidies requiring academic and industry partners cooperation) that incentivize partnerships can promote academia-industry innovation collaboration. Thirdly, organizing workshops and seminars that bring together academia and industry experts could facilitate the exchange of knowledge and ideas. This can lead to the development of new research projects and collaborations, and establishing technology transfer offices within academic institutions can promote academia-industry partnerships for innovation. These offices can identify potential industry partners, negotiate intellectual property

agreements, and facilitate technology and knowledge transfer from academia to industry.
Lastly -but certainly not least- civil society, which encompasses patient advocacy groups and the general public, plays a crucial role in the neurosurgery technology market. They can impact the acceptance and utilization of neurosurgical robotics and advocate for regulations prioritizing patient safety and accessibility. Moreover, civil society can offer insights to industry and policy stakeholders by sharing patient needs and concerns, informing decision-making and promoting better outcomes for patients and the wider community. Table 3, "*Global Neuro- health Societies for Common Neurological Illnesses*," lists societies focusing on common neurological illnesses.
The table shows that societies from the United States, Europe, and Australia are the most prevalent, with the United States having the highest representation (7 out of 25). In terms of the primary objectives of the societies, several themes are repeated frequently, including promoting awareness and education about neurological disorders, supporting research, and advocating for patient rights and access to care. Other objectives include providing resources and support for patients and families, improving clinical care, and collaborating with other organizations and stakeholders.

The neurosurgery innovation system analysis through the Quadruple Helix model allowed us to delimit and determine the key areas in the innovation-driven neurosurgery devices market: neuroendoscopy, implantable drug delivery systems, neurovascuscular catheters, surgical instruments, invasive neurostimulation and neurosurgical robotics. Said areas were elaborated on under section 3 of this report regarding their market value and impact on society. Hopefully, the report has shed some light and provided guidance about this under-researched and complex field. This report has explained the evolution of neurosurgery devices market and its potential as one of the fastest-growing medical markets in the foreseeable future. The leading players of the area have been identified, as well as the key areas for innovation. Those interested in the reading might get a more profound understanding of the field that might revolutionize medical surgery.

Robotic surgery is still in its early stages of development and adoption in neurosurgery. However, robotic-assisted surgery has the potential to revolutionize the way neurosurgeons approach complex surgical procedures, improving precision, safety, and efficiency in neurosurgery, which can lead to better patient outcomes, reduced complications, and shorter hospital stays. In addition, as the global population ages and the prevalence of neurological disorders such as Parkinson's disease increases, the demand for neurosurgical procedures is expected to rise. This growing demand for neurosurgical procedures, combined with the potential benefits of robotic surgery, is driving the growth of the neurosurgery devices market. The innovation ecosystem for neurosurgery robotics is complex and multidisciplinary, involving several factors, such as technological capabilities, regulatory frameworks, market demand, and clinical evidence. Therefore, understanding the market trends, key players, technological advancements and their interplay in the neurosurgery devices market is crucial for healthcare providers, manufacturers, investors, and policymakers to make informed decisions, drive innovation, and ensure the safe and effective implementation of RAS technologies in neurosurgery.

The research conducted in this report suggests that the adoption of robotic-assisted surgery in neurosurgery is growing, driven by its accuracy, control, and visualization advantages. The market is expected to grow at a compound annual growth rate (CAGR) of 13%, reaching USD 13.5 billion by 2024. Furthermore, the analysis of the market share by region reveals that North America and Europe dominated the market in 2019, with North America holding a 43% market share and Europe holding a 38.4% market share. However, the Asia Pacific region is expected to experience a significant increase in market share by 2024, reaching 23.75%. The field of neurosurgical robotics is relatively less competitive, making it an attractive option for entry, although some countries may present regulatory challenges. There is ample opportunity for technological progress in this field and a high demand for such technology. However, this report has also identified several challenges and obstacles to overcome in order to integrate robotic surgery into the neurosurgery innovation system, including the high cost of these systems, limited access to training and expertise, and the need to adapt existing surgical workflows to accommodate these technologies. Addressing these challenges will require close collaboration between stakeholders, including hospitals, universities, and industry, to develop innovative solutions and ensure robotic surgery technologies' safe and effective implementation in neurosurgery.

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Appendix A

Table A1 Series

Table A1 was divided into three tables: A1.1 for big companies, A1.2 for SMEs, and A1.3 for startups in neurosurgery, neurosurgical robotics, or other engineering or computing areas (i.e., ML, AI) that work in the domain of neurosurgical robotics or one of the identified neurosurgery areas.

Table A1.1

Big Companies in Neurosurgery and Neurosurgical Robotics

Company	Country	Specialty	Description
Zimmer Biomet Robotics	France	Minimally invasive, robotics, and neurosurgery.	Zimmer Biomet, founded in 1927, is a publicly traded medical device firm. They developed the ROSA ONE Brain, a robotic platform that aids surgeons in the planning and execution of difficult neurosurgery operations in a minimally invasive manner.
Intuitive Surgical	US	Surgical robotics, and minimally invasive.	In 2018, Intuitive Surgical maintained its dominance in the US robotic surgery market. It received FDA certification for its first-historically robotic system, da Vinci®, in 2000, and since then, they have used the da Vinci® framework to build a robotic surgery empire. Other da Vinci® systems, such as the da Vinci S® and the da Vinci Si®, were introduced in 2006 and 2009, respectively, while Intuitive's Clagship product, the da Vinci Xi®, was introduced in 2014. Intuitive Surgical will

			continue to be the market leader for a long time, thanks to revenue from surgeries, services, and maintenance fees.
Stryker	US	Catheters, cranial instruments, and orthopedic surgical robotics.	Stryker has two neurotechnology categories, cranial and neurovascular. Following their acquisition of MAKO Surgical Corp for $1.65 billion in 2013, Stryker was the second biggest challenger in the robotic surgery market. MAKO developed and marketed the Rio® Robotic Arm interactive orthopedic surgical platform, which Stryker now refers to as the MakoTM Robotic Arm. The MakoTM framework, which is used for partial knee and absolute hip arthroplasty, generates the vast majority of revenue in the orthopedic robotics business.
Vicarious Surgical	US	Minimally invasive, surgical robotics, and VR.	The company was founded in 2014. Vicarious Surgical Robotic System is built with abdominal access and visibility through a single port in mind. Vicarious Surgical reported in August 2020 that it has raised $13.2 million in investment, on top of the tens of millions already raised in prior years. The Cambridge, Massachusetts - based business is looking to develop

			and commercialize its robotics and virtual reality technology for minimally invasive surgery.
Brainlab AG	Germany	Neurosurgery, spine surgery, orthopedic surgery, cranial robotics, mixed reality (XR), and brain mapping.	Founded in 1989, BrainLAB is a big company dedicated to developing truly revolutionary software that will harness physicians' expertise in order to provide patients with consistently better, more standardized, and cost- effective healthcare. BrainLAB aspires to be the top provider of software for both minimally invasive therapies and cancer therapy.
DePuy Synthes	Switzerland	Craniomaxillofacial (CMF), spine surgery, and orthopedic surgery.	Founded in 1999, and acquired by Johnson & Johnson in 2012. It is a global medical device manufacturer headquartered in Solothurn, Switzerland, and West Chester, Pennsylvania, USA. DePuy Synthes has one of the world's most extensive orthopedic portfolios. In addition to the VELYSTM Digital Surgery portfolio, DePuy Synthes solutions in specialties such as joint reconstruction, trauma, craniomaxillofacial, spinal surgery, and sports medicine are designed to advance patient care while delivering clinical and economic value to health care systems worldwide.
Integra LifeSciences	US	Neurosurgery, reconstructive surgery,	Integral Life Sciences,

		brain mapping, and electrosurgery.	headquartered in Princeton, New Jersey, is a global leader in medical technology that was created in 1989 with the acquisition of an engineered collagen technology platform used to repair and regenerate tissue. Integra's regenerative technology product line has since grown to encompass surgical equipment, neurosurgery products, and advanced wound care items. Integra is a global leader in neurosurgery, with a diverse product and solution portfolio for dural access and repair, cerebral spinal management, and neuro- critical care. Their regenerative tissue technologies encompass soft tissue, nerve, and tendon repairs, as well as solutions for the treatment of acute and chronic wounds, burns, and plastic and reconstructive surgery.
Penumbra	US	Neurovascular, acute ischemic stroke, brain aneurysm, embolization catheter, access catheter, and neuroendoscopy.	Penumbra, Inc. founded in 2004 creates therapeutically useful solutions to aid individuals suffering from stroke and neurovascular illness. It provides the Penumbra System, an ischemic

			stroke device platform; the Penumbra Coil 400, which allows for rapid aneurysm packing; the 5MAX ACE, a clot extraction device for engaging and removing blood clots that cause an acute ischemic stroke; and the Neuron System, a family of access catheters that allow therapies to be delivered to blood vessels high up in the brain.
Nihon Kohden	Japan	Electroencephalographs, evoked potential, electromyographsystems, electrocardiographs, defibrillators, and hematology analyzers.	Nihon Kohden corporation, founded in 1951 is Japan's leading manufacturer, developer, and distributor of medical electronic equipment, with operations in the United States, Europe, and Asia, as well as distributors in almost every country on the planet.
Renishaw plc	UK	Neurosurgery, stereotactic neurosurgery, surgical robotics, DBS, SEEG and DDS.	Renishaw founded in 1973 is a multinational corporation with primary competencies in measurement, motion control, spectroscopy, and precision machining. They provide novel products that greatly improve their customers' operational performance, such as increasing production efficiencies and product quality, as well as maximizing research capacity and boosting the

			efficacy of medical operations. Machine tool automation, coordinate measurement, additive manufacturing, gauging, Raman spectroscopy, machine calibration, position feedback, CAD/CAM dentistry, shape memory alloys, large scale surveys, stereotactic neurosurgery, and medical diagnostics are all applications for their products.

Table A1.2

Small-to-Medium sized Enterprises (SMEs) in Neurosurgery and Neurosurgical Robotics

Company	Country	Specialty	Description
Synaptive Medical	Canada	Neurosurgery, robotics, automation, point-of-care MRI, digital microscopy, and brain tractography.	Synaptive Medical is a global medical device and technology company with over 350 employees and was founded in 2012. Synaptive Medical Develops GPS-Like Suite of Neurosurgery Tools.
XACT Robotics	Israel	Radiology, and robotics.	XACT Robotics® is a privately held corporation that was established in 2013. This SME is committed to revolutionizing the field of radiology by creating the world's first and only hands-free robotic systems that can increase targeting precision, efficiency, and consistency in percutaneous radiology treatments.
Neuralink	US	BCI and robotics	The Neuralink Corporation is a neurotechnology startup co- founded by Elon Musk in 2016. They are an SME that creates implanted brain-machine interfaces and due to the high precision needed to implant the leads of the chip, they developed a surgical robot.
Activ Surgical	US	Imaging, laparoscopy, and minimally invasive.	Activ Surgical founded in 2017 offers the ActivEdge Surgical Intelligence Platform, their one product, transforms intraoperative surgical imaging by collecting highly contextualized data analytics that

			enable faster video data annotation for machine-learning-driven intraoperative surgical intelligence.
Monteris Medical	US	Minimally invasive, robotics, and MRI-guided instrument.	Monteris Medical was established in 1999 with the primary purpose of assisting patients suffering from neurological illnesses. The company's mission remains the same: to develop a less invasive surgical procedure for use in the brain. They recently revealed in September 2020 that it has raised an additional $9 million, just four months after passing the 3,000-person mark with their NeuroBlate robot-assisted brain surgery equipment.
Medrobotics	US	Robotic and minimally invasive.	Medrobotics founded in 2005 is a Massachusetts-based company that has received a US$20 million investment to expand into general medical surgery and develop cutting-edge robotic devices. The Flex® Robotic System, the world's first endoluminal robotic platform with a steerable and shapeable robotic scope. Its Flex Robotic System received FDA certification in 2015 and allows clinicians to access anatomical locations such as the ear, nose, or throat using its snakelike design and 180° route. In July 2015, Medrobotics got FDA authorization for the Flex® Robotic System

			for ENT applications, and in May 2017, for transanal applications. In March of 2014, the CE mark was issued.
Diligent Robotics	US	Autonomous robots and AI.	Diligent Robotics founded in 2016 offers AI-powered robots that are able to collaborate with humans in everyday situations. The organization's autonomous Moxi robot can be left alone in hospitals to handle time-consuming logistical tasks such as setting up patient rooms and restocking supply rooms. Moxi is even filled with social intelligence that is transmitted through its head motions and LED eyes, making it suitable for navigating hospital hallways and other restricted settings.
GanyMed Robotics	France	RAS, Orthopedic surgery, and AI.	Founded in 2018, Ganymed Robotics creates superior artificial intelligence and robotics technology for orthopedics. Its objective is to improve patient outcomes, surgeon experience, and total joint replacement intervention efficiency. Ganymed Robotics has created a one-of-a-kind robot-with-eyes platform that allows surgeons to see beyond the naked sight and make the ideal motion.
MicroSure	Netherlands	Microsurgery and surgical robotics.	In 2016, Eindhoven University of Technology and Maastricht University Medical Center created Microsure, a

			medical device firm. MUSA, the world's first surgical robot for open microsurgery, is their current product. MUSA was developed in close collaboration with microsurgeons and engineers for microsurgical purposes. MUSA enables microsurgeons with superhuman precision, enabling new procedures that are currently difficult to conduct by hand. Currently the robot is used for three types of surgeries, lymphatic surgery, hand surgery, and free Clap surgery.
THINK Surgical	US	Surgical robotics and orthopedic surgery - joint replacement surgery.	THINK Surgical®, Inc. was founded in 2007. It designs, produces, and markets active robotics for knee replacement surgery and maintains an open implant library to provide surgeons with the most options for their patients. The TSolution One® Total Knee Application was approved by the FDA in October 2019 and is now available for purchase in the United States and other countries.
Verb Surgical	US	Big data, machine learning, and surgical robotics.	Verb surgical founded in 2015 is the world's most innovative robotic surgery group, formed as a strategic cooperation between Google's Alphabet and Johnson & Johnson's medical equipment business, Ethicon. They are focusing on developing a digital surgery platform that

			combines robotics technology, advanced visualization, advanced instruments, and data analytics. Such robotic surgery startups use Google's big data and machine learning expertise to build a digital surgical platform that will be less expensive than current medical robots.
Corindus	US	Robotic-assisted intervention.	Corindus, founded in 2001 and acquired by Siemens Healthineers in October 29, 2019. Corindus is the world leader in robotic-assisted vascular treatments. The CorPath® platform from the Company is the first FDA-approved medical device to bring robotic precision to percutaneous coronary and vascular operations. CorPath GRX is a second-generation robotic-assisted technology that adds crucial key updates to the platform that increase precision, improve work flow, and expand the capabilities and variety of treatments that may be performed robotically. The CorPath 200 device is designed for percutaneous coronary interventions. The CorPath is used in

			conjunction with a radiation-protected "cockpit" for the surgeon. The CorPath 200 is the first and only robotic-assisted technique that uses an optimized interventional cockpit to control the placement of coronary guidewires and stent/swell catheters. The surgeon uses the framework to work CorPath 200 from behind a radiation-protected "cockpit." Instead of being with a patient while wearing a lead apron, the surgeon sits behind an operating station, managing surgical gear with a variety of touch-screen and joystick controls.
Microport Medbot	China	Surgical robotics.	MicroPort MedBot founded in 2014 is the only surgical robot firm in the world with a product portfolio that includes laparoscopic, orthopedic, panvascular, natural orifice, and percutaneous surgical procedures, currently has one authorized product and eight in the pipeline.
AdEchoTech	France	Ultrasound imaging, telemedicine, and robotics.	Ad Echo Tech is a small-to- medium-sized French firm based near Paris that has been partially supported by the CNES (French Agency for Space Studies). Dr. Efric Lefebvre, a well-known ultrasonic radiologist, launched it

			in 2008. It introduced the first multi-purpose tele-ultrasound robot. Their expertise stems from more than 15 years of space medicine research.
Myomo	US	Orthosis, paralysis solution,and robotics.	Myomo, Inc. founded in 2004 is a medical robotics company that provides increased movement for those with neurological diseases including upper-limb paralysis. Myomo develops and markets the Myo Pro ® product line of light weight, non-invasive, powered arm braces to restore function in paralyzed or weakened arms and hands of individuals who have suffered a stroke, spinal cord or nerve injury such as brachial plexus injury, or other neuro-muscular disability such as amyotrophic lateral sclerosis (ALS) or multiple sclerosis (MS). Myomo's MyoPro controlled brace is meant to assist persons who have experienced a loss of motion or debilitating in their hands and arms as a result of a variety of diseases. The device analyzes nerve impulses from the skin's surface before activating small engines that promote natural arm and hand movements.
Tamar Robotics	Israel	Neurosurgery, spine surgery, head and neck procedures, thoracic surgery, minimally invasive, and surgical robotics.	Tamar Robotics founded in 2018 is developing an endoscopic surgical robotic system that will allow the benefits of minimally invasive

			robotic surgery to be realized in "small cavity" treatments in Neurosurgery, Spine, Head & Neck, Urology, and Thoracic surgery. Because of their "arm and elbows" kinematics, current single port robotic systems necessitate a vast working space. As a result, they are predominantly used in abdominal, prostate, and gyn surgery.
Mazor Robotics	Israel	Spine surgery, surgical robotics, and surgical navigation system.	Founded in 2001 and acquired by Medtronic in 2018, Mazor Robotics is a spine surgery pioneer that makes surgery safer for patients, doctors, and OR personnel. Renaissance, Mazor Robotics' innovative guidance system, is revolutionizing spine surgery from freehand operations to highly accurate, cutting-edge treatments that improve clinical results.
Simbionix	US	Surgery training simulators.	Founded in 1997, and acquired by Surgical Science in 2021. Surgical Science is the world's leading provider of innovative medical professional and healthcare industry partner training and education solutions. Innovative research and development, cutting-edge technology, and strong clinical ties encourage the use of best medical practices, increase clinical performance, and optimize

			procedural outcomes. Surgical Science's simulators, which include the clinically approved Simbionix simulator product line, have been installed worldwide for more than 20 years.
Titan Medical	Canada	RAS, surgical robotics, and single access surgery.	Founded in 2008, Titan Medical is dedicated to the development of robotic-assisted technology for use in single-access surgery. With twin 3D and 2D high-definition vision systems, multi-articulating instruments, and an ergonomic surgeon workstation, they are developing our Enos system to become the new standard of care in robotic single access surgery.
Covariant	US	Robotics and AI	Covariant is a non-medical device startup founded in 2017 creates robots that understand general abilities such as robust 3D sensing, physical affordances of objects, few-shot learning, and real-time motion planning. This enables them to adapt to new tasks in the same way that humans do, by breaking difficult tasks down into basic steps and applying general skills to execute them. Among the many industries they are involved in, healthcare is among them.
MediRobot	Spain	Artificial vision and robotics.	MediRobot is a non-medical device R&D&I industrial engineering firm out of Alicante specializing in factory

			modernization with over 30 years of experience.
Auris Health	US	Endoscopy, robotics, bronchoscopy, lung cancer, and urology.	Auris Health is an SME composed of 130 employees founded in 2007 and recently acquired by Ethicon, part of the J&J medical device companies in April of 2019 for $3.4 billion. They created the MONARCH platform, a mobile robotic cart, which improves existing minimally invasive procedures by adding robotics into the equation.
Brain Corp	US	AI and robotics.	Brain Corp founded in 2009 develop artificial intelligence (AI) software for developing and deploying autonomous mobile robots (AMRs) such as robot scrubbers and delivery tugs that can assist people in dynamic public spaces such as grocery stores, retail stores, airports, hospitals, malls, universities, and others. As of now, they have deployed over 16000 autonomous robots.
Immersion Corporation IMMR	US	Haptic feedback.	Immersion envisioned taking personal computing one-step further when it was founded in 1993. The in-depth investigation into the then-experimental realm of sensory technology began to alter the way people interacted with their devices. The resulting haptic feedback technology quickly became popular

			among customers worldwide. They are currently involved in the gaming, automotive, and cellphones industry.
Robust AI	US	Robotics and AI	Robust AI founded in 2019 is developing AI tools that will allow robots to better comprehend people and work with them. Combining AI, robotics, and human-centered design to build robots that are generally useful, easy to adopt, and enjoyable to use. As of now Robust AI have a total funding of $22.5M.
Wise	Italy	Neuromonitoring and neuromodulation.	WISE Srl is a medical device firm based in Milan and Berlin that is creating a new generation of implantable leads for neuromonitoring and neuromodulation. Their proprietary process enables the fabrication of stretchable and flexible electrodes on medical-grade elastic polymers.

Table A1.3

Startup in Neurosurgery and Neurosurgical Robotics

Company	Country	Specialty	Description
[CMR Surgical]	UK	Surgical robotics and minimally invasive.	CMR Surgical, a unicorn startup founded in 2014 headquartered in Cambridge with around 500 employees. CMR Surgical is a British company that is developing Versius, a cutting- edge delicate surgical robotic system for low access medical surgery. Their objective is to make minimally invasive medical procedure widely available and affordable. They received the European CE Mark for their Versius Surgical Robot in March 2019.
[Zeta Surgical]	US	Image-guidance, XR, computer vision, AI, robotics, and neurosurgery.	Zeta Surgical is a startup and SME founded in 2018. Zeta Surgical creates surgical navigation and robotics solutions in order to make minimally invasive surgeries easier, faster, and more accessible. Zeta, their navigation and robotics platform, enables surgeons to operate on completely awake patients at the point-of-care. Currently, they are using their abilities in neurosurgery.
[HOZ Medical]	China	Surgical robotics, minimally invasive, and neurosurgery.	HOZ Medical, founded in 2000 in Beijing, is a developer of neurosurgical robots. It is focused on the clinical use of frameless

			stereotactic radiosurgery in neurosurgery, as well as the development of medical robots for craniocerebral surgery.
Omniscient Neurotechnology	Australia	Brain mapping.	Omniscient Neurotechnology is a groundbreaking brain mapping startup founded in 2019 that is using data to revolutionize brain care. Their solutions are useful for neurosurgeons in that they provide accurate understanding of a patient's specific brain networks for practical surgical insights prior to life-changing surgery. Researchers can benefit from them as their technologies analyze massive amounts of neural data to deliver valuable structural and functional information tailored to each subject.
Realtime Robotics	US	R obotics, automation, and AI.	Realtime Robotics is a startup and SME founded in 2016. With the help of their platform an expert can design, test, deploy, run, and collaborate their robotic projects. They work in the automotive, logistics, and electronic industries. For now, they have three products, the Realtime Controller, RapidPlan software, and RapidSense.
Proximie	UK	AI, machine learning and Aug mented Reality (AR).	Founded in 2016 by the influential Lebanese plastic surgeon, Dr. Nadine Hachach-Haram, Proximie is a technology platform

			that allows clinicians from anywhere in the world to virtually 'scrub in' to any operating room or lab. Proximie enables numerous persons in different locations to digitally interact in the same way they would if they were working in the same operating room. It means they may physically show one other where to make an incision or use bodily gestures to demonstrate a procedure in real time. Currently, their total funding amounts to $38M.
Avatar Medical	France	Virtual reality (VR).	Avatar Medical, a startup founded in 2020 employs virtual reality and Bayesian techniques to enable ultra-fluid navigation within patient avatars based on medical images. No data preprocessing is required for compatibility with all tomographic image type. The innovative technology of this company enables clinicians to change patient representations in real-time and virtual reality.
Robeauté	France	Microrobot, neurosurgery, and internal brain navigation.	Robeauté is a startup founded in 2017. They design surgical microrobots that are smaller than a rice grain. Robeauté microrobot, which has been designed specifically for the brain and will be used by neurosurgeons, will be able to freely

			traverse through other complicated parts of the body to do biopsies, collect accurate anatomically localized data, and give medicines on site, at the proper dosage. They are accompanying a significant change from robotic surgery to microrobotic surgery in order to achieve more precision, better results, and bold new therapeutics to combat global diseases that afflicts over a billion people globally.
Hemerion Therapeutics	France	Brain tumor surgery and photonics treatment.	Hemerion® is a French start-up committed to the development of innovative cancer medicines. Hemerion's innovations and know-how are the outcome of over ten years of academic and clinical research at the University of Lille, the University Hospital of Lille, and Inserm. Hemerion's principal emphasis is on developing novel treatments for glioblastoma, the most frequent and aggressive primary brain tumor.
Pipra	Switzerland	AI and neurosurgery	Pipra or Pre-Interventional Preventive Risk assessment is a startup founded in 2019. Pipra's AI- based technology enables pre- surgical screening and exact risk assessment, which will

			help to reduce post-op cognitive damage in the elderly. They currently have a funding of €1.3M.
Predictheon	Spain	Anesthesia, pre- op care, AI and data analysis.	Predictheon is a startup founded in 2019. Predictheon's solutions are algorithms that use mathematical models encoded in software and may be used in a variety of platforms, such as clinical monitors, infusion pumps, and electronic health records. A processing system that receives and analyses real-time clinical inputs from patients, mathematical models/algorithms that conduct predictions, and an intuitive display of predictions that are updated constantly over time. Their main solutions are based on a sophisticated data analysis engine that employs population analysis, predictive analytics, nonlinear mixed-effects modeling, and data science approaches that include Artificial Intelligence. It has closed its first round of investment for an amount of €840,000.
Med Robots	Portugal	AI, robotics, and automation.	Med Robots' goal is to find demands in the healthcare logistics business that may be

			fulfilled by robotic devices. Their mission is to improve patient stays in hospital settings by delivering cutting-edge integrated logistics solutions. Hospitals can be more productive with their technology, and health care professionals can focus on what is most important: the well-being of patients. Med Robots developed an autonomous UV-C disinfection robot that uses Ultraviolet light with wave lengths ranging from 200 to 300 nm to damage the DNA structure of viruses, bacteria, yeasts, and fungus in seconds. They plan to use automation, AI, and social robots to improve the logistic and repetitive process of hospitals.
InformAI	US	Machine learning, AI, and image recognition.	InformAI founded in June 2017 develops business analytics and artificial intelligence-based solutions for industry-leading healthcare organizations, medical device makers, and imaging/ PACS providers in order to improve mission outcomes and operational efficiency. The organization offers computer consultancy, artificial intelligence-based software solutions for image classification, natural language processing for operative procedures, and

			prediction algorithms for mission-critical applications. The AI software developed by the company allows for faster patient diagnosis at the point of care and improved patient outcomes and risk analyses.
Neurallys	France	Implanted sensors and remote patient monitoring.	A young startup that was created in February 2016 and was incubated at the Brain and Spine Institute. Neurallys is developing a one-of-a-kind solution to improve the quality of life for hydrocephalus patients, enrich the care offered, and develop tailored treatment. It will finally be feasible to suggest improved management of the disease, which promises to help thousands of patients, thanks to its mini-invasive "barometer" sensor that continuously detects and records intracranial pressure.
NeuraMedica	US	Neurosurgery and orthopedic surgery.	NeuraMedica is an early-stage startup based at Oregon Health and Science University (OHSU) founded in 2014 that is working on the development of a unique, bioabsorbable surgical clip for durotomy closure.

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