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A Bibliometric Analysis of Intraoperative Neuromonitoring in Spine Surgery

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Key words
- Bibliometry
- Intraoperative neuromonitoring
- IONM
- MEP
- Spine surgery
- SSEP

Abbreviations and Acronyms
IONM: Intraoperative neuromonitoring
IONMS: Intraoperative neuromonitoring in spine surgery
MCP: Multiple-country publication
MEP: Motor-evoked potentials
SCP: Single-country publication
WoS: Web of Science

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Intraoperative neuromonitoring (IONM) techniques are usually implemented during spine surgery to avoid nefarious abuse of the nervous system, which can cause postoperative problems. A lack of bibliometric analysis on the topic of IONM in spine surgery has been identified. Therefore, the aims of this study are to provide information about the main contributors to this field and their publication dynamics, as well as conceptual and cooperative networks. Results have shown that a steady publication increase has been occurring since 1991, with high levels of citations in the first decade, but irregular publication rates have been recorded more recently. Research production by country seems to be in line with what is observed in other surgical fields, but research funding for IONM in spine surgery seems to be lower, even with the clear interest of private funding agencies. The conceptual networks have shown the importance of motor-evoked potential, electromyography, and the effect of anesthesia, particularly in scoliosis surgery.

INTRODUCTION

Spine surgery can be a complex procedure, not only because of the challenges of the structures being operated on but also because of the risks it presents to patients, especially when additional instrumentation is required.[1]

Intraoperative neuromonitoring (IONM) has been used for several decades with the objective of ensuring that surgery is successful, with minimal postsurgery impairment to the patient. Its objective is to evaluate the electric activity of relevant pathways and detect potential nefarious abuses to the nervous system.[2] Different modalities can be used, such as somatosensory-evoked potentials, motor-evoked potentials (MEP), and electromyography,[3] in a continuous or intermittent manner.[4] These techniques may even be used simultaneously to improve sensitivity and specificity during IONM in spine surgery (IONMS) of different natures.[5]

Aside from the state of the art provided by literature reviews, analysis of scientific production and citation dynamics may prove a useful tool in understanding the state of a scientific field. The use of bibliometric techniques to analyze large volumes of information allows the observation of patterns and dynamics otherwise obfuscated and unveils new levels of information.[6] Bibliometric studies have been presented for several biomedical fields, or for the publication output of specialty journals,[7] but this type of analysis is still scarce.[8] Just a few bibliometric studies have been published in spine surgery,[8-12] and to the best of our knowledge, no studies are available on the use of IONMS, thus presenting a clear absence of information.

The objective of this study is to provide a bibliometric analysis of the use of IONMS in scientific production, thus showing the main contributors and identifying conceptual and cooperation networks and their dynamics.

METHODS

A database search was conducted on March 1, 2021 in the Clarivate Analytics Web of Science (WoS). A topic search was performed containing the following keywords: (Intraoperative AND neuro* AND *monitoring AND spin*). The results were filtered to include only journal articles published in English until the year 2020. The full record and cited references were retrieved.

The resulting data were further analyzed using the Bibliometrix toolbox,[13] and its graphic user interface Biblioshiny, in RStudio 1.4.1106 (RStudio Inc., Boston, Massachusetts, USA) for descriptive and quantitative analysis of data. This process included the extraction of data set information, documents, and authors and sources information, as well as their dynamics. Research categories and funding information were retrieved from the WoS built-in citation analyzer because of its easier access. The VOSViewer[14] was used for bibliometric networks analysis, including the calculation of keywords co-occurrence, country collaboration, and authors' bibliographic coupling. Whenever information had to be ranked, the top 10 elements were reported, except for the sources, where the core sources are used independently of their number. For the purpose of temporal segmentation, 3 decades were considered: 1991–2000, 2001–2010, and 2011–2020.

RESULTS AND DISCUSSION

Publication Dynamics in IONMS

A total of 1006 documents, encompassing the period between 1991 and 2020, were retrieved. These documents included 967 full articles (96.12%), 6 early access articles (0.59%), and 33 proceeding articles (3.28%). These articles were published by corresponding authors from 43 different countries, of which 24 (55.8%) were in Europe, 11 (25.6%) in Asia, 5 (11.6%) in the Americas, 2 (4.7%) in Oceania, and the remaining 1 (2.3%) in Africa.

Although a large number of authors were identified ($n = 4031$), 79.4% ($n = 3203$) of these authored a single article, 12.7% ($n = 512$) authored 2 articles, and only 3.6% ($n = 145$) had 3 articles in their name, meaning that <4.3% ($n = 173$) have authored ≥4 documents. Articles are usually coauthored by 4.09 researchers, as denoted by the collaboration index.[6] On the other hand, only 26 articles (2.6%) were authored by a single researcher.

The retrieved data set presented publications in 10 different WoS categories. Most articles are within the clinical neurology (69.3%) category, followed by surgery (37.7%), orthopedics (32.0%), neurosciences (14.6%), anesthesiology (7.9%), pediatrics (6.9%), medicine general internal (3.8%), cardiac cardiovascular systems (2.2%), medicine research experimental (2.1%), and respiratory system (1.6%).

The number of published articles presents an overall average annual growth rate[15] of about 14.6%, which is mirrored by the number of total citations, as shown in Figure 1A. During the first decade (1991–2000) the average annual growth was 12.0%, which almost doubled to 22.1% in the following decade (2001–2010). However, the last decade (2011–2020) has seen a decrease to an average rate of 9.5%. Years with an increase of ≥50% in published articles compared with the previous year may be identified in 2002 (50.0%), 2007 (90.9%), 2009 (84.2%), and 2016 (52.1%).

In terms of overall citation dynamics, each document has received an average of 18.9 citations, with 1.53 citations per article per year. This value has varied along the decades, with each document receiving an average of 36.42 citations and 1.43 citations per article per year during the first decade. During the second decade, a similar number of citations per article (35.6) was registered, along with an increase in citations per article per year (2.32). Starting in 2009, the number of citations per article has been steadily decreasing, and for this reason, in this last decade, each article received only 8.1 citations and 1.2 citations per year per document.

Journals Dynamics

A total of 227 distinct journals were identified as publishing articles in IONMS. This number has substantially increased from the 51 journals in the first decade and 80 in the second decade, doubling in the last decade ($n = 165$). However, the core sources according to the Bradford law[16] include only 6 journals: *Spine*, *European Spine Journal*, *Journal of Neurosurgery: Spine*, *Journal of Clinical Neurophysiology*, *World Neurosurgery*, and *Clinical Neurophysiology*. This set of journals account for 34.8% of all publications in this IONMS data set. Figure 2 presents the number of published articles in each of the core journals since 1991, compared with the sum of articles published by these sources.

Most Relevant Authors, Articles, and Citations

The most productive authors were analyzed by the number of documents they authored in this data set, whereas the most cited authors were analyzed by the total number of citations received. The 10 most productive authors have authored between 12 and 22 articles, which represents 1.2%–2.2% of the total scientific production. From this list, half are also present in the top 10 most cited authors, as described in Table 1.

The most cited articles were retrieved and ranked by the number of local citations, but global citations are also presented to calculate the ratio between both. Local citations are the number of times a given article has been cited by the documents in the data set of this study, whereas global citations include all the citations that an article received according to the WoS database. As listed in Table 2, Schwartz et al.[17] and Hilibrand et al.[18] are tied in terms of local citations ($n = 93$), but Schwartz et al. gather more citations outside this data set ($n = 191$ vs. 186).

Sala et al.,[19] Langeloo et al.,[20] and Dawson et al.[21] are also tied in terms of

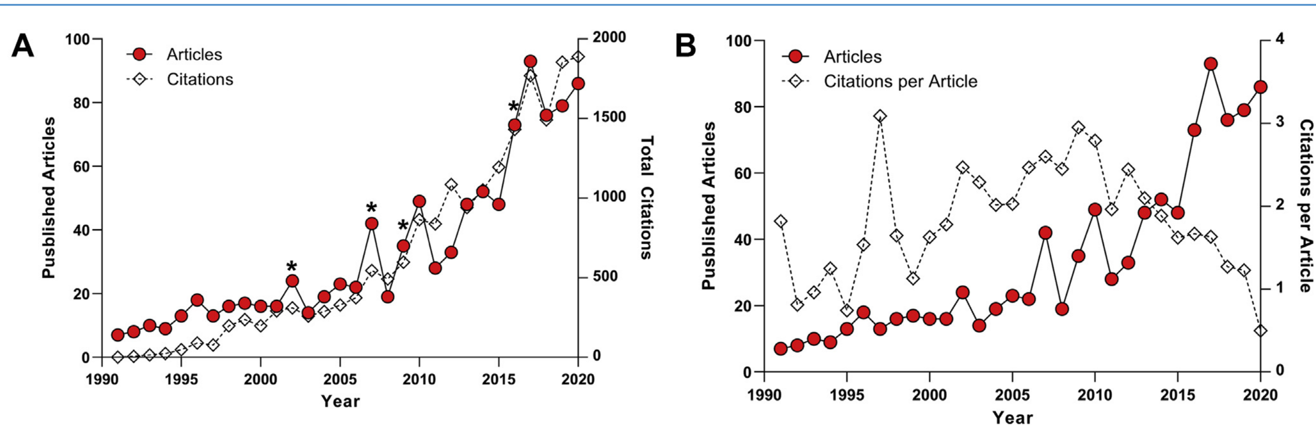

Figure 1. Variation of the number of (**A**) total published articles and total citations and (**B**) total published articles and the citations per article in the same period. * indicates years in which an annual growth ≥50.0% was observed.

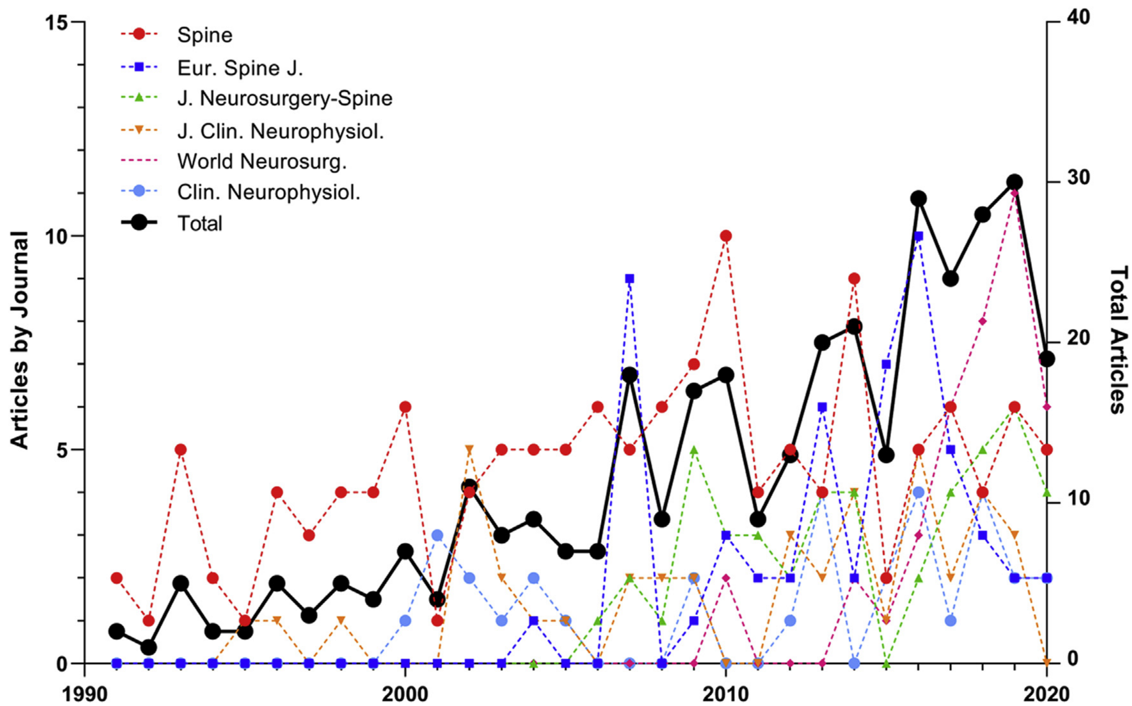

Figure 2. Number of articles published in each of the 6 core journals since 1991 and comparison with the sum of all the articles published by the core sources.

local citations. The 4 most cited articles are all related to the use of transcranial electric MEP and somatosensory-evoked potentials during surgery and, therefore, are the seminal works in this field. Two of the listed articles are related to an inspection of the state of the field. Dawson et al.[21] presented a survey reporting the surgical outcomes of using IONM as experienced by the members of the European Spinal Deformity Society, whereas McDonald et al.[24] presented the recommendations, endorsed by the American Society of Neurophysiological Monitoring, for the use of MEP as IONM. Both these articles show the interest in understanding current knowledge and the need to establish consensus and guidelines that can be used to minimize postsurgical complications, but may also allow more reproducible research.

Worldwide Distribution and Cooperative Networks

The cooperation among countries in academic research can be analyzed in terms of the corresponding author nationality compared with the remaining authors. This strategy allows the categorization of an article as a product of a single-country publication (SCP), when all authors share the same nationality, or a multiple-country publication (MCP), when ≥1 author has a different nationality.[6] The 10 most productive countries in terms of articles, and their distribution as SCP or MCP, are summarized in Table 3.

The United States accounts for most (41.2%) of all published articles, mostly as SCP but with a moderate amount of MCP. China and Japan appear as second and third, respectively, with a similar number of articles, but distinct percentage of MCP articles. From the top 10 countries, Germany, Canada, and Italy are those with most relative MCP, with an MCP/SCP ratio >27.7%. When comparing the production by continent, North America accounts for 45.3%, Asia for 21.0%, and Europe for 14.9% of total publications.

The coauthoring analysis by country showed 18 countries sharing at least 10 articles, as shown in Figure 3. The United States has a central position in terms of coauthorship, which agrees with its dominance of published articles. Its strongest links are with Canada, Germany, and Italy. These countries, which have a high MCP count, seem to be hubs of cooperation, sharing links with other countries.

Research Funding

Research funding analysis is often overlooked, but an analysis of public and private funding may show how appealing the field may be for investments, especially by the private sector. The top 10 funding agencies were retrieved and categorized according to Amiri et al.[27] and are listed in Table 4.

From the information available in the data set analyzed in this study, 823 articles (81.8%) did not report any funding agency. The listed agencies have financed 18.2% ($n = 183$) of the articles in IONMS, with public funding accounting for 73.2% ($n = 134$) of the investment, 20.2% ($n = 37$) from the industry sector, and the remaining 6.6% ($n = 12$) from a foundation.

Conceptual Structure

To identify the most relevant author keywords, a co-occurrence analysis was performed. A total of 133 of 2002 (6.64%) keywords appeared together ≥5 times. Four clusters with a minimum of 20

Table 1. List of the Ten Most Prolific and the Ten Most Cited Authors, Along with their Research Impact Expressed as h-Index

Most Productive Authors				Most Local Cited Authors			
Author	**Affiliation**	**Number of Documents (% of Total)**	**h-Index**	**Author**	**Affiliation**	**Number of Citations**	**h-Index**
Lenke LG	Columbia University Medical Center	22 (2.2)	16	Schwartz, DM	Surgical Monitoring Associates	287	10
Deletis V	Albert Einstein College of Medicine	19 (1.9)	14	Lenke LG	Columbia University Medical Center	274	16
Imagama S	Nagoya University Graduate School of Medicine	17 (1.7)	8	Bridwell, KH	Washington University School of Medicine	234	12
Fehlings MG	University of Toronto	16 (1.6)	8	Lyon R	University of California	222	12
Lyon R	University of California	15 (1.5)	12	Fehlings MG	University of Toronto	219	8
Matsuyama Y	Hamamatsu University School of Medicine	14 (1.4)	8	Deletis V	Albert Einstein College of Medicine	217	14
Ando K	Nagoya University Graduate School of Medicine	13 (1.3)	6	Padberg AM	Barnes-Jewish Hospital	216	10
Ishiguro N	Nagoya University Graduate School of Medicine	13 (1.3)	8	MacDonald DB	King Faisal Specialist Hospital	182	9
Tian Y	Peking Union Medical College Hospital	12 (1.2)	6	Calancie B	SUNY Upstate Medical University	167	8
Bridwell KH	Washington University School of Medicine	12 (1.2)	12	Dvorak J	Schulthess Clinic	165	7

keywords each were identified and are depicted in **Figure 4**.

The first cluster (*red*) is the largest with 45 keywords. Based on total link strength, "intraoperative neuromonitoring," "intraoperative neurophysiologic monitoring," and "scoliosis" are the most relevant attributes, giving an apparent relation to "intraoperative neuromonitoring in scoliosis." The second cluster (*green*) comprises 35 items with "somatosensory evoked potentials," "motor evoked potentials," and "spine" as the strongest links, indicating a relation with the theme of "motor evoked potentials." The thirst cluster (*blue*), with 31 items, shows strong links with "intraoperative monitoring" and "electromyography," thus representing a thematic cluster of "electromyography monitoring." The fourth cluster (*yellow*) presents 22 items, of which "motor evoked potential" has the strongest link. This keyword was already found in other clusters. However, "propofol" and "anaesthesia" appear next, indicating that this cluster is concerned with the "anaesthesia effect in motor evoked potentials."

When the average publication year of the keywords with strongest link in each cluster are analyzed, differences are observed. For the cluster "intraoperative neuromonitoring in scoliosis" (*red*), the average publication year ranges from 2004 to 2018; "motor evoked potentials" (*green*) between 2004 and 2017; "electromyography monitoring" (*blue*) between 2001 and 2016 and "anaesthesia effect in motor evoked potentials" (*yellow*) between 2003 and 2017.

Intellectual Structure

The bibliographic coupling of authors was analyzed with a network comprising authors with >4 articles. This criterion was met by 151 authors, allowing the construction of the network in **Figure 5**, featuring 4 clusters.

The first and larger cluster (*red*) includes 55 authors, of whom Calancie, Deletis, and Lyon are those with higher citations and total link strengths. The second cluster (*green*) encompasses 52 authors, with Schwartz and Fehlings with most citations. The third cluster (*blue*) includes Ito and Matsuyama as most cited, and the fourth cluster (*yellow*) has Lenke as most cited, followed by Bridwell. However, the temporal dynamics of these citations show that the Calancie, Deletis, Lyon cluster (*red*) tends to include articles published before 2000. Schwartz and Fehling (*green*) is a transition cluster because it includes publications between 2007 and 2018. The Lenke (*yellow*) cluster ranged between 2011 and 2018. The Ito and Matsuyama (*blue*) cluster includes citations of articles published between 2013 and 2018 and, thus, is the most recent.

DISCUSSION

The bibliometric data from this study present the first insight into the state and dynamics of article publication in IONMS. The number of articles retrieved and analyzed was relatively small ($n = 1006$), considering the range of documents found in other bibliographic studies in spine surgery.[8,12,28] However, although these studies analyzed the entire field of spine surgery, this study focused on the use of IONM. The small number of documents is also a result of the analysis being limited to articles, regardless of the type of research being reported. Early access articles were considered, because they are representative of newly added

Table 2. Most Cited Articles, Ordered by the Number of Local Citations, and Comparison with the Global Citations Count

First Author (Year)	Title	Local Citations	Global Citations	LC/GC Ratio (%)
Schwartz et al., 2007[17]	Neurophysiological detection of impending spinal cord injury during scoliosis surgery	93	191	48.7
Hilibrand et al., 2004[18]	Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery	93	186	50.0
Sala et al., 2006[19]	Motor evoked potential monitoring improves outcome after surgery for intramedullary spinal cord tumors: a historical control study	76	219	34.7
Langeloo et al., 2003[20]	Transcranial electrical motor-evoked potential monitoring during surgery for spinal deformity: a study of 145 patients	76	149	51.0
Dawson et al., 1991[21]	Spinal cord monitoring. Results of the Scoliosis Research Society and the European Spinal Deformity Society survey	76	139	54.7
Pelosi et al., 2002[22]	Combined monitoring of motor and somatosensory evoked potentials in orthopaedic spinal surgery	72	147	49.0
Fehlings et al., 2010[23]	The evidence for intraoperative neurophysiological monitoring in spine surgery: does it make a difference?	69	136	50.7
McDonald et al., 2013[24]	Intraoperative motor evoked potential monitoring—a position statement by the American Society of Neurophysiological Monitoring	65	175	37.1
McDonald et al., 2003[25]	Monitoring scoliosis surgery with combined multiple pulse transcranial electric motor and cortical somatosensory-evoked potentials from the lower and upper extremities	56	109	51.4
Calancie et al., 1998[26]	"Threshold-level" multipulse transcranial electrical stimulation of motor cortex for intraoperative monitoring of spinal motor tracts: description of method and comparison to somatosensory evoked potential monitoring	54	161	33.5

knowledge, as were proceeding articles, because these have been reported to be equivalent to regular articles in terms of structure and impact.[29]

The number of authors per article is lower than the 6 reported by Farhan et al.[30] for publications in neurosurgery and the 5 reported by Wei et al.[12] for spine surgery.

Table 3. Most Frequent Country of Origin of the Corresponding Author in single-country publications and Multiple-Country Publications

Country	Number of Documents (% of Total)	SCP (%)	MCP (%)	MCP/SCP Ratio
United States	414 (41.2)	375 (90.6)	39 (9.4)	10.4
China	74 (7.4)	69 (93.2)	5 (6.8)	7.2
Japan	72 (7.2)	71 (98.6)	1 (1.4)	1.4
Germany	60 (6.0)	47 (78.3)	13 (21.7)	27.7
South Korea	43 (4.3)	41 (95.3)	2 (4.7)	4.9
Canada	41 (4.1)	30 (73.2)	11 (26.8)	36.7
Italy	41 (4.1)	32 (78.0)	9 (22.0)	28.1
Switzerland	27 (2.7)	24 (88.9)	3 (11.1)	12.5
Netherlands	21 (2.1)	18 (85.7)	3 (14.3)	16.7
Turkey	21 (2.1)	19 (90.5)	2 (9.5)	10.5

SCP, single-country publication; MCP, multiple-country publication.

However, the number of coauthors is expected to increase. As IONMS advances, so its complexity is expected to increase, requiring research teams with more diverse skills and competences, and therefore larger.[31] On the opposite side of this effect are single-authored articles, which are expected to become even fewer in the upcoming years.[31] That prediction seems to be accurate, because this study found an apparent decreasing trend of such articles between the first ($n = 9$) and last ($n = 7$) decade.

From its inception, IONMS has presented a steady increase in publications, although not every annual increase was positive. During the first decade, the average annual increase was 12.0%, which almost doubled to 22.1% in the following decade. However, the last decade has seen a decrease to an average rate of 9.5%. This is the result of unstable publication dynamics in the last decade, with highly productive years followed by a decrease in publication, thus resulting in a lower average annual increase. Despite this instability, the last

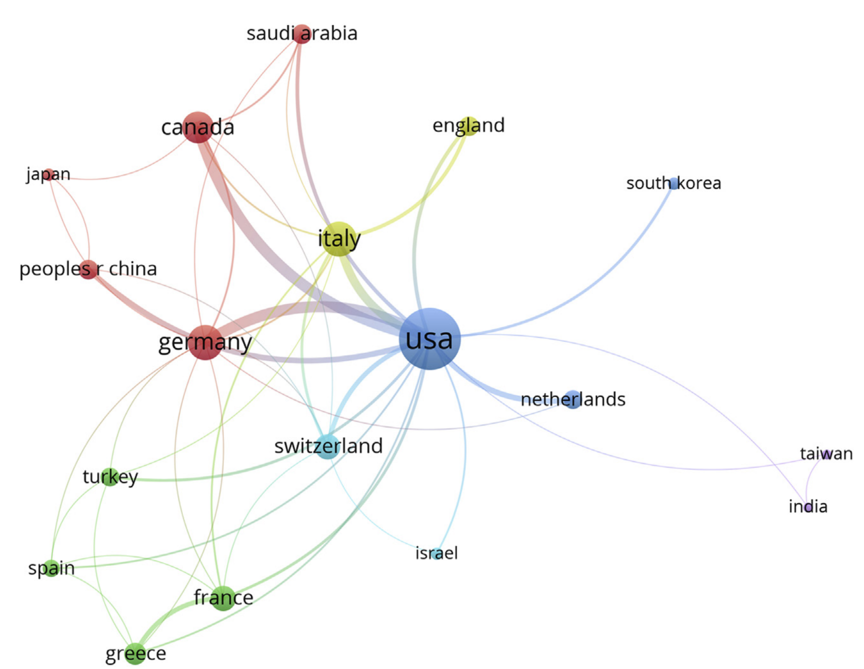

Figure 3. Coauthorship network by country. *Different colors* represent different collaborative clusters, whereas the *line thickness* is proportional to the link strength.

decade alone accounts for 61.2% ($n = 616$) of all published articles in IONMS.

Although the total citation numbers seem to mirror the published articles, starting in 2009, the number of citations per article has been steadily decreasing. Farhan et al.[30] reported similar numbers for the first and second decade in neurosurgery, albeit this study shows a slower decrease in the total citations per article.

The higher number of citations per article in the first 2 decades of publication on IONMS may be related to the existence of relatively few articles from which to draw information or even to the publication of highly valuable articles, citation of which may be needed. This process does not necessarily evaluate the quality of the article because the reason for citation is not known. Garfield[32] listed 15 reasons to cite an article, including the acknowledgment of pioneers of original publications, identifying methodologies or equipment, substantiating claims or findings, or discussion of one's own or other findings. What is known is that authors cite useful works. Thus, citations indicate a measure of usefulness, impact or influence of a publication,[33] but do not necessarily evaluate its quality or rigor. Some articles, even if consulted, are never cited, and citations are usually biased to established authors or documents. Therefore, the increase in published articles and the establishment of authors most relevant to IONMS may lead to the citation decrease observed during the last decade. Although it is tempting to analyze if the high number of citations per article is related to a given document, it is important to understand that studies require at least 2–5 years to accumulate enough citations to be used as a reliable bibliometric indicator.[33-35] Choosing an adequate time frame of 2, 3, or 5 years may yield different results.

Another reason that may be related to a decrease in citation is the spread of

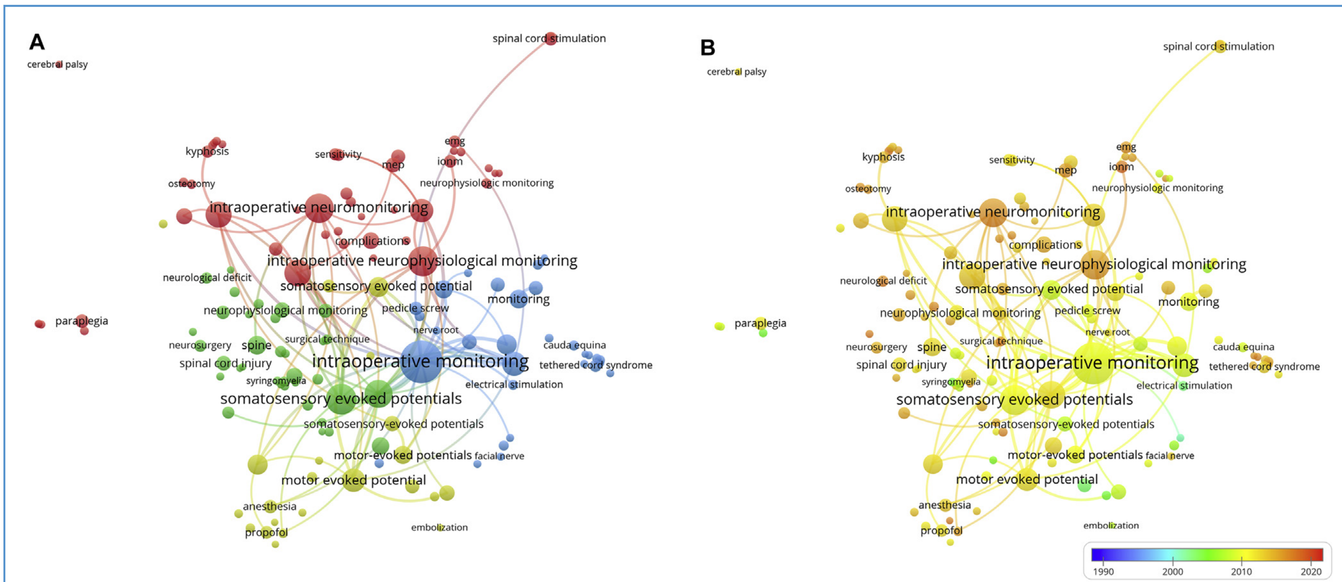

Figure 4. Representation of the keyword co-occurrence network in terms of (**A**) cluster identification with links with a minimum strength of 5 and (**B**) the average publication year of each keyword. *Larger diameter circles* correspond to greater co-occurrence of a given keyword.

Table 4. Funding Agencies with More Reports of Funding, their Headquarters Country, and Business Nature

Funding Agency	Country	Category	Records (% of Total)
National Institutes of Health	United States	Public	84 (8.3)
Japan Society for the Promotion of Science	Japan	Public	24 (2.4)
DePuy	United States	Industry	14 (1.4)
Medtronic	Ireland	Industry	13 (1.3)
Ministry of Education, Culture, Sports, Science and Technology of Japan	Japan	Public	13 (1.3)
National Natural Science Foundation of China	China	Public	13 (1.3)
AO Spine	Greece	Foundation	12 (1.2)
Nuvasiv	United States	Industry	5 (0.5)
PFIZER	United States	Industry	5 (0.5)

publications across different journals. This study identified only 51 journals in the first decade, which represents fewer sources from which to gather information. In the last decade, the number of journals increased to 165, meaning that relevant information is no longer concentrated in a few selected journals. Because each journal may require different subscriptions, access to information may not be available to all researchers.

Despite the large number of periodicals, just 6 journals account for 34.8% of the total number of publications. Although they may not be representative of the research published in many other journals, they are representative of the research being conducted in IONMs[8] and therefore a good indication of its dynamics.

Each journal presents a particular publication trend along the years. *Spine* was the first journal dedicated to research in spine research,[36] and along with *Journal of Clinical Neurophysiology* was among the first to publish articles in IONMS. Both these journals accounted for most publications in the first 2 decades, with the latter being responsible for spurs of publication in 2007 and 2017. The third decade has seen a democratization among journals, with each journal increasing their publications. The last years of this decade registered a steady decrease in *European Spine Journal*, in opposition to an increase of *World Neurosurgery* and *Journal of Neurosurgery: Spine*.

Nevertheless, and despite the journal dynamics and impact, all had a decline in 2020 publications. The severe acute respiratory syndrome coronavirus 2 pandemic may be responsible for this decrease, disrupting the normal research process[37] and requiring the diversion of funds, resources, and personnel to other tasks. This situation is particularly understandable in medical research, because professional imperatives have changed. On the other hand, a shift in research and publication priorities may have occurred, because the published research in this disease may be without precedents.[38]

The accumulated knowledge in the field is the result of several authors. Only a few have a significant impact, either because of their high productivity, endowing the researcher with more sources of information, or because of the usefulness and impact of their research, which leads to community recognition in the form of citations. A measure of an author's importance is not readily available, usually being

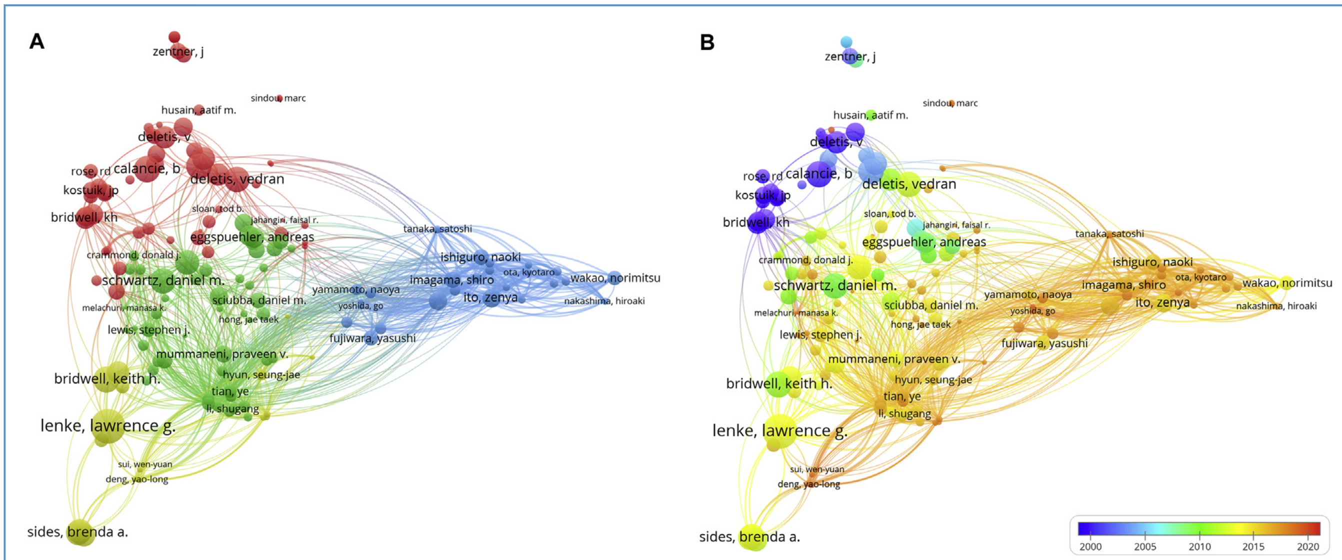

Figure 5. Bibliographic coupling of authors as its visualization in terms of (**A**) citations and (**B**) citations per average publication year. *Larger diameter circles* indicate authors with more citations.

the use of indicators, such as the impact factor,[39] h-index and m-quotient,[40] or the g-index.[41] Although the limitations of the h-index are known and extensively reported,[42-44] it still is the most popular and widely used ranking metric and for this reason was selected for this study.

According to Sandström and van den Besselaar,[45] highly productive authors have more chances of becoming highly cited as well. In this data set, we have found that prolific authors are not always among the most cited. Only prolific authors with an h-index >10 are present in the top 10 most cited authors. On the other hand, some of the most cited authors have a lower h-index, which may indicate a smaller body of scientific work but with higher impact,[43] or being in an early stage of their academic or professional carrier.

This h-index value may be a good indicator of the impact of a researcher in IONMS, because Spearman et al.[42] reported that the median h-index in neurosurgery was 9, with higher values associated with higher academic positions.[42,46] However, caution is advised when comparing h-index among different research fields, because they may not be comparable.[40] Because this is, to the best of our knowledge, the first time that the h-index has been calculated in IONMS, a comparison with similar medical fields is necessary.

None of this study's top cited authors is listed in any study reporting the top 100 most cited articles in lumbar spine surgery[47] or in neurosurgery.[7,48] Only Hilibrand and Lenke are among the 100 most cited articles in spine research,[36] with articles not related to IONMS but rather to degenerative diseases and deformities, respectively.

Two reasons may have contributed to this fact: not enough time has passed to allow IONMS publications to accumulate citations, or IONMS is still a niche field within spine surgery. The first hypothesis is a possibility, because the 3 most cited IONMS articles listed in this study have higher citations than the 100th article ($n = 176$) reported by Steinberger et al.,[47] but they had 6 years to accumulate more citations since the publication of the study by Steinberger et al.[47] However, the second hypothesis is more likely, because spine research includes fields as diverse as neurosurgery, orthopedics, anesthesiology, and radiology.[36] When querying the bibliographic databases for spine surgery, themes such as back pain,[28,47] degenerative spine diseases and trauma,[36] and biomechanics[28] dominate the results, leaving IONMS and other niche field articles out of the rank.

An important factor in scientific advancement is the sharing of knowledge, in which cooperation among researchers from different countries is a valuable factor. This study has identified the most productive countries and analyzed their level of cooperation by the number of articles published with foreign researchers. The rank and publication proportions of the countries are similar to those found in previous bibliometric analysis in spine surgery,[12] atlantoaxial spine surgery,[11] and lumbar spinal stenosis, with the United States leading in terms of published articles, and China, Japan, and Germany following. The stronger links of Germany, Canada, and Italy with the United States seem to indicate that they share with this country a large part of their MCP.

From the information available in this study's data set, 823 articles (81.8%) did not report any funding agency, which is higher than the two thirds reported by Wei et al.[12] and by Amiri et al.[27] in spine research. Institutions, either public or industrial, from the United States are among the most enthusiastic in funding research, followed by Japan and China. The National Institutes of Health is the institution with most investment in the field, which is 3.5 times higher than Japan's investment. Although Ireland is listed because it hosts Medtronic's headquarters, this company was created in the United States, where it develops most of its activity and where it is listed in the New York stock exchange.[49] Greece, on the other hand, is hosting AO Spine, albeit that this association has an international scope. Therefore, the presence of these countries on the list does not necessarily reflect a particular investment interest from these countries, but rather the administrative location of a company.

Although this study has not explored in depth the effect of funding on scientific production, Amiri et al.[27] reported that industry-funded spinal research has a significant association with favorable outcomes and level IV evidence. Further studies are required to understand if that association is extensible to IONMS, although this study indicates the ability of IONMS to attract private funding.

The conceptual clusters identified highlight that IONMS is an important technique during scoliosis surgery, mostly based on the use of MEP and electromyography as a measurement of detection. The high sensitivity of MEP to anesthesia[2] explains why this cluster has a range of average publication year comparable to that of the MEP cluster. Other than that, the broad range of publication year seems to indicate that the conceptual cluster has not changed considerably in the past 29 years. An exception may be found when looking at the average publication year of each keyword. Although intraoperative monitoring has a greater co-occurrence, keywords with synonyms including the prefix neuro-are found in more recent publications.

The bibliographic coupling provides an interesting insight in to how the work of different authors has influenced different periods of IONMS research. The Calancie, Deletis, and Lyon cluster presents the basic research in the field, because their names are associated with older publication dates. On the other hand, the works of the Ito and Matsuyama cluster are more recent and have many within-cluster links, as well as links with other bibliographic clusters. It is expected that this cluster will represent a larger role in upcoming publications.

CONCLUSIONS

The use of IONM techniques is important for achieving positive outcomes during spinal surgery. The continuous growth of publication denotes that this field is active, although not necessarily innovating. The average publication year of articles has shown small variations across the conceptual clusters. Innovative conceptual clusters, with recent average publication years, have not been identified. These dynamics were found in terms of bibliographic coupling, indicating that the main researchers may be changing or shifting their research interests.

The absence of the most productive or cited authors reported in this study in the top 100 ranks in spine surgery and neurosurgery may indicate that the field is yet to become a preponderant part of spine surgery. This factor may also be related to the apparent lack of innovation, and to a niche application in scoliosis and other related surgeries.

The dominance of the United States in terms of publication seems to be to the result of the high level of financial support by funding agencies, either public or private. Therefore, this field may be attractive for funding agencies, although it is still less financed than overall spine research. Increased funding may solve some of the lack of innovation, because surgical and neurophysiologic research entails expensive equipment and procedures.

This study provides an overall insight in to the publication dynamics in IONMS and also shows the need for more bibliographic analysis. Studies focused on other aspects of IONMS may shed light on some of the aspects that this study was unable to clarify because of the lack of comparative information.

LIMITATIONS

This bibliometric analysis was focused on the records of WoS and did not include complementary information from other highly regarded databases. Different databases present different content overlap, with Scopus reportedly having >20% unique material compared with WoS and covering the entire MEDLINE (PubMed) database.[50] However, there are reports of a lack of standardization of Scopus references, with duplicated entries,[51,52] missing publications,[53] and the fact that differences in indexation among databases can lead to the same information being presented differently.[54] Also, in terms of funding agency identification, there is a significant difference among databases, with WoS having the most consistent results.[55] All these issues have the potential to bias this bibliometric analysis.

Although WoS is not free of issues, the problems with Scopus accuracy and consistency, allied to the challenges of a successful and effective merge of different databases, led to the selection of WoS for this study.

All secondary sources, such as reviews, were excluded because they are based on primary sources. However, only articles were considered as primary sources. This strategy left other potentially relevant documents, such as letters, case reports, and books, out of the scope of this analysis. This strategy was adopted because these documents are usually associated with low levels of evidence[56] or are not peer reviewed.

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