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Deep brain stimulation from past to future: research trends and global outcomes with bibliometric analysis during 1980-2022

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ABSTRACT

Aims: We aimed to summarize the intellectual structure of the deep brain stimulation (DBS), to reveal the global productivity, to identify and map the latest trends by analysing the social and structural relationships between the different research components of scientific articles published on DBS.

Methods: 5939 articles on DBS published during 1980 and 2022 were analysed utilized various statistical approaches. Network visualization maps were created to reveal trend topics, citation analysis, and international collaborations. Spearman's correlation analysis was used for correlation investigations. The exponential smoothing predictor was used to determine the article productivity trend.

Results: The most prolific author on DBS was Okun, Michael S. (209 articles) and the most productive institution was the University of Toronto (n=283). The top 3 productive countries were United States of America (n=2371, 39.9%), Germany (910, 15.3%), and United Kingdom (550, 9.2%). From past to present, the most studied topics were Parkinson's disease, subthalamic nucleus DBS, dystonia, globus pallidus, essential tremor, movement disorders, thalamus, functional neurosurgery, neuromodulation, depression, obsessive compulsive disorder, basal ganglia.

Conclusion: The primary trend topics that have been studied more in recent years are tractography, freezing of gait, Parkinson's disease, Parkinson&#8217, Parkinson#apos, autonomy, self, machine learning, non-motor symptoms, functional connectivity, globus pallidus interna, volume of tissue activated, adaptive deep brain stimulation, beta oscillations, medial forebrain bundle, and local field potential. The secondery trend topics were optogenetics, pediatric, frameless, closed-loop DBS, refractory epilepsy, satellite broadcasting, asleep DBS, optimization, biomarker, directional Leeds, nucleus bassals of meynert, personality, authenticity, and anterior nucleus of thalamus.

Keywords: Deep brain stimulation, deep brain stimulator, DBS, research trends, bibliometric analysis

INTRODUCTION

The clinical use of deep brain stimulation (DBS), which presents new therapeutic possibilities for neurological and psychiatric disorders, is one of the most important developments in clinical neurosciences in the last 20 years. DBS is a brain surgery procedure consisting of the implantation to specific targets within the brain of electrodes which allow targeted circuit-based neuromodulation, and the provision of fixed and intermittent electricity from an implanted battery source.[1,2] The basic principle of DBS is to use a small eletrode to transmit electrical impulses to focal brain regions.[2] Since receiving approval from the Food and Drug Administration (FDA) and Conformité Européene (CE), DBS has become a care standard in Parkinson's disease, essential tremor, and dystonia, and it is also being actively investigated for other neurological and psychiatric diseases linked to a pathological circuit, including major depressive disorder, Alzheimer's disease, obsessive-compulsive disease, Tourette syndrome, anorexia nervosa, epilepsy and schizophrenia.[2,3]

Parkinson's disease (PD) is one of the chronic neurological diseases that lead to the most disability and significant levels of loss in quality of life. There are various drugs with which the disease symptoms can be effectively treated, but long-term medical treatment is complicated because of motor complications that develop, generally due to levodopa.[4] Increasing neuronal activity in the subthalamic nucleus (STN) and the pars interna of

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the globus pallidus is thought to be responsible for the impaired motor function in patients with Parkinson's disease.[5] DBS of the STN and pars interna of the globus pallidus is currently the most common therapeutic surgical procedure for PD patients with no response to medical treatment. Neurostimulation has been shown to improve motor activity and daily living activities in advanced PD, but there may be cognitive side-effects such as impulsivity.[4-9]

Together with the emergence of DBS in the treatment of PD and tremor, a natural desire has arisen to attempt DBS for dystonia.[10,11] Some studies have shown that DBS improved mood in treatment-resistant depression and obsessive-compulsive disease.[12] Following those findings, the mechanisms of DBS started to be actively investigated for several different neurological and psychiatric diseases. The history of DBS is an influential example of the interaction between fundamental and clinical research. Current understanding is that DBS activates neurons and regulates pathological activity and expressions in the basal ganglion thalamocortical network, and this improves sensorimotor processing and relieves disease symptoms.[3]

Although the effect mechanisms of DBS have not been fully understood at the cellular, molecular and system level, developments in DBS technology are without doubt expected to expand the scope of application and provide additional clinical and scientific benefits.[1,2] Nevertheless, despite the advantages, DBS continues to be an invasive surgical intervention with low but potentially severe risks, including bleeding and infection.[1,2] It is thought that with new developments such as closed circuit stimuli and optogenetic stimuli, DBS will become a multidirectional treatment strategy.[3]

Bibliometric analysis is a comprehensive method that has become popular in recent years, which uses various statistical approaches to analyse a relatively greater amount of scientific data.[13,14] Bibliometric analyses enable high impact articles to be revealed and show emerging trends of the research subjects, while also contributing to the evaluation of the evolutionary process of a specific area.[15,16] In parallel with the need to analyse the increasing number of publications in literature, many bibliometric studies have been conducted on different subjects.[13-17]

As yet, there is no comprehensive bibliometric study in literature on the topic of DBS. The aim of this study was to summarise the intellectual structure of the topic of DBS by analyzing the social and structural relationships between different research components (countries, institutions, authors, topics) of scientific articles published on the topic of DBS between 1980 and 2022, and to determine the global productivity and recent trends with mapping.

METHODS

This study does not contain any studies with human participants or animals performed by any of the authors. For this type of study ethics committee approval is not required. All procedures were carried out in accordance with the ethical rules and the principles.

Research Strategy

The Web of Science (WoS) Core Collection by Clarivate Analytics database was used to access the articles on DBS. Since articles before 1980 were not indexed in WoS, the search start period was determined as 1980 and the end time was determined as 2022. As a result of the publication search on DBS, all studies with the phrase deep brain stimulation/stimulations, deep brain stimulator/stimulators or DBS were found (Considering that the abbreviation DBS can also be used in different research areas, studies that used the phrase DBS in the title and also the phrase deep brain stimulation/stimulator in the abstract section of the article were included). Repeatability codes for researchers to obtain similar documents (access date: November 15, 2022, search findings may vary depending on different access dates): ((TI="deep brain") AND (TI=stimulation*)) OR ((TI="deep brain") AND (TI=stimulator*)) OR ((TI=DBS) AND (TS=deep brain stimulation*)) OR ((TI=DBS) AND (TS=deep brain stimulator*)).

Statistical Analysis

VOSviewer (Version 1.6.18, Leiden University) software was used for bibliometric network visualizations, mapping of international academic collaborations and citation analysis.[18] Exponential Smoothing estimator, which also takes into account seasonal correction, was used in the Microsoft Excel software to predict the trend of articles in the coming years by using the number of articles published in the past on DBS. The world map was drawn using the open access website (https://app.datawrapper.de). Statistical analyses were performed with SPSS (Version: 22.0, SPSS Inc., Chicago, IL, USA, License: Hitit University) software. Before the correlation analyses, the conformity of the data to the normal distribution was examined with the Kolmogorov-Smirnov test. The relationship between the productivity of the articles on DBS and the Gross Domestic Product (GDP) and GDP per capita values, which are the economic size indicators of the countries, were determined by Spearman correlation analysis (data extracted from the World Bank website[19]). For the statistical significance limit, $P<0.05$ was accepted.

RESULTS

A total of 12511 publications related to DBS, which were indexed in WoS and published between 1980 and 2022, were obtained through the literature review. The

distribution of these publications is Articles (5939, 47.5%), Meeting Abstracts (3591, 28.7%), Review Articles (926, 7.4%), Letters (743, 5.9%), Proceedings Papers (585, 4.7%), and the rest are other publications types (Editorial Materials, Book Chapters, News Item, Book Review, Book, Data Paper, Discussion, Note). Bibliometric analyses were performed with 5939 articles indexed only in the Article publication category out of a total of 12511 publications. 97.3% (n=5780) of these articles were published in English and the rest were published in other languages (German (n=79), Spanish (25), French (18), Polish (11), Hungarian (7), Czech (6), Japanese (4), Portuguese (3), Turkish (2), Chinese (1), Esperanto (1), Italian (1), Korean (1)). Almost all of the articles were indexed in SCI-Expanded (n=5379, 90.6%), Emerging Sources Citation Index (ESCI) (n=313, 5.3%) and Social Sciences Citation Index (SSCI) (n=67, 1.1%).

Research Areas with the Most Published Articles on DBS

The research areas with the highest number of articles published on DBS (research areas with 70 or more articles published) are Clinical Neurology (n=3236, 54.4%), Neurosciences (2211, 37.2%), Surgery (1394, 23.4%), Psychiatry (468, 7.8%), Neuroimaging (434, 7.3%), Engineering Biomedical (251, 4.2%), Medicine Research Experimental (232, 3.9%), Radiology Nuclear Medicine Medical Imaging (187, 3.1%), Multidisciplinary Sciences (183, 3.0%), Psychology (152, 2.5%), Medicine General Internal (141, 2.3%), Behavioral Sciences (95, 1.6%), Rehabilitation (94, 1.5%), Pharmacology Pharmacy (86, 1.4%), Engineering Electrical Electronic (72, 1.2%), and Pediatrics (71, 1.1%) (An article can be found in more than one research area).

Development of Publications by Years and Future Publication Trend on DBS

The line graph showing the distribution of the number of articles published on DBS by years is presented in Figure 1. Since 2022 is not completed, it is not included in the forecast model. In order to determine the number of articles that can be published in 2022 and beyond, our estimation values for the results obtained with the Exponential Smoothing estimator by performing seasonal adjustment are shown in Figure 1. According to the estimation model results, it is estimated that 573 (Confidence Interval %: 530-616) articles will be published in 2022 and 707 (CI%: 560-854) articles will be published in 2026 (Figure 1).

Productive Authors on DBS

The main active authors in the production of scientific papers (with 65 or more articles published) on DBS were Okun MS. (n=209), Foote KD. (162), Lozano AM. (154), Volkmann J. (102), Deuschl G. (90), Visser-vandewalle V. (82), Krauss JK. (81), Limousin P. (78), Aziz TZ. (77), Hamani C. (77), Starr PA. (77), Zrinzo L. (75), Mcintyre CC. (74), Timmermann L. (73), Kuhn AA. (70), and Temel Y. (65), respectively.

Main Productive Institutions that have published the Most Articles on DBS

The most active institution addresses mentioned in more than 100 articles on DBS were University of Toronto (n=283), State University System of Florida (260), University of California System (258), University Toronto Affiliates (256), University of Florida (242), Udice French Research Universities (237), University of London (236), University Health Network Toronto (234), University of Cologne (196), Institut

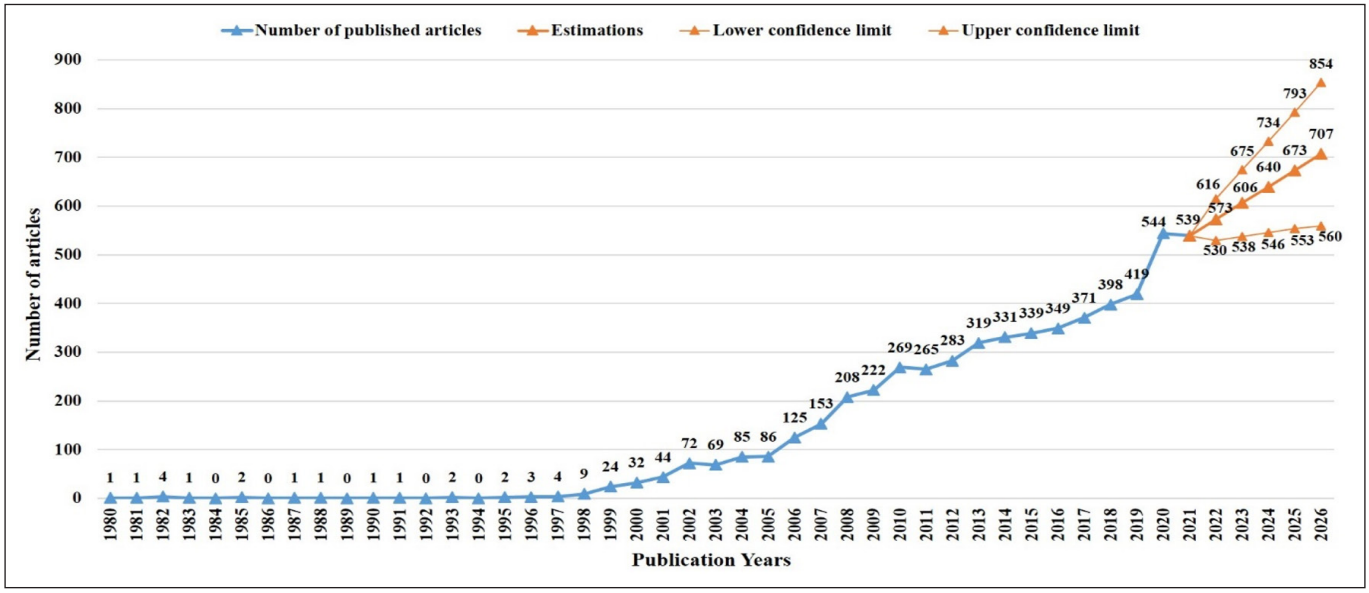

Figure 1. Bar graph showing the distribution of published articles on deep brain stimulation (DBS) over time, with a forecast for the next five years.

National De La Sante Et De La Recherche Medicale (195), University College London (190), Cleveland Clinic Foundation (187), Harvard University (168), University of Oxford (163), Humboldt University of Berlin (160), Free University of Berlin (159), Charite Universitatsmedizin Berlin (155), University of California San Francisco (151), Mayo Clinic (140), University of Amsterdam (128), Centre National De La Recherche Scientifique (127), University of Kiel (122), University of Minnesota System (112), Case Western Reserve University (110), University of Minnesota Twin Cities (110), Harvard Medical School (108), Emory University (106), Baylor College of Medicine (104), and US Department of Veterans Affairs (101), respectively.

Productive Journals on DBS

5939 articles published on DBS were published in 875 different scientific journals. Among these journals, the first 56 most productive journals that have published 20 or more articles on DBS, the total number of citations received by the journals and the average number of citations per article were shown in Table 1.

Productive Countries on DBS

The colour density map showing the distribution of the number of articles by countries and the bar graph showing the top 20 most productive countries were presented in Figure 2. The top 20 most productive countries contributing to the literature on DBS were the United States of America (n=2371, 39.9%), Germany (910, 15.3%), United Kingdom (550, 9.2%), Canada (428, 7.2%), China (420, 7%), France (371, 6.2%), Italy (320, 5.3%), Netherlands (279, 4.6%), Switzerland (202, 3.4%), Japan (188, 3.1%), Spain (176, 2.9%), South Korea (173, 2.9%), Sweden (173, 2.9%), Australia (154, 2.5%), Brazil (114, 1.9%), Belgium (84, 1.4%), Turkey (76, 1.2%), Taiwan (72, 1.2%), Poland (66, 1.1%), and India (57, 1%). Cluster analysis was conducted among 59 countries that published at least two articles from 78 countries that published articles on DBS and whose authors had international collaboration, and the findings are shown in Figure 3.a. According to the cluster analysis findings, it was determined that international cooperation on DBS was divided into 10 different clusters. In addition, international cooperation analysis was carried out among 59 countries and

Table 1. The 56 most productive journals with 20 or more articles on deep brain stimulation

Journals	NA	C	AC	Journals	NA	C	AC
Stereotactic and Functional Neurosurgery	290	6107	21.1	Tremor and other Hyperkinetic Movements	41	238	5.8
Movement Disorders	254	13945	54.9	Journal of the Neurological Sciences	40	684	17.1
Journal of Neurosurgery	209	9272	44.4	Journal of Neuroscience Methods	39	896	23.0
Parkinsonism & Related Disorders	197	4081	20.7	Operative Neurosurgery	39	338	8.7
Neuromodulation	175	2417	13.8	Journal of Neural Transmission	37	705	19.1
Brain Stimulation	132	3415	25.9	Parkinsons Disease	37	360	9.7
World Neurosurgery	130	1642	12.6	Neurological Sciences	36	697	19.4
Neurosurgery	122	5908	48.4	Annals of Neurology	34	3300	97.1
Acta Neurochirurgica	116	2239	19.3	Journal of Neurophysiology	34	2001	58.9
Journal of Neurology Neurosurgery and Psychiatry	99	6855	69.2	European Journal of Neurology	31	848	27.4
Plos One	89	2079	23.4	IEEE Transactions on Neural Systems and Rehabilitation Engineering	31	744	24.0
Frontiers in Human Neuroscience	86	769	8.9	British Journal of Neurosurgery	29	468	16.1
Neurology	84	7944	94.6	Nervenarzt	29	169	5.8
Journal of Clinical Neuroscience	77	1356	17.6	Neuroimage-Clinical	29	586	20.2
Journal of Neural Engineering	77	2543	33.0	Journal of Neuroscience	28	1871	66.8
Journal of Neurology	76	2262	29.8	Neuroethics	28	593	21.2
Frontiers in Neurology	70	323	4.6	Behavioural Brain Research	27	414	15.3
Clinical Neurology and Neurosurgery	65	814	12.5	European Journal of Neuroscience	27	934	34.6
Neuroimage	56	2715	48.5	Deep Brain Stimulation in Neurological and Psychiatric Disorders	26	67	2.6
Brain Sciences	55	271	4.9	Turkish Neurosurgery	26	132	5.1
Clinical Neurophysiology	53	2500	47.2	European Journal of Paediatric Neurology	25	467	18.7
Frontiers in Neuroscience	51	582	11.4	Neuroscience	24	392	16.3
Movement Disorders Clinical Practice	51	332	6.5	Biological Psychiatry	23	4150	180.4
Neurosurgical Focus	50	1345	26.9	Epilepsia	23	1055	45.9
Experimental Neurology	44	1926	43.8	Neurobiology of Disease	22	421	19.1
Journal of Parkinsons Disease	44	349	7.9	Neurologia I Neurochirurgia Polska	21	143	6.8
Scientific Reports	42	366	8.7	IEEE Transactions on Biomedical Engineering	21	581	27.7
Brain	41	4381	106.9	Neuroscience Letters	20	503	25.2

NA: Number of article, C: Number of citation, AC: Average number of citations per article

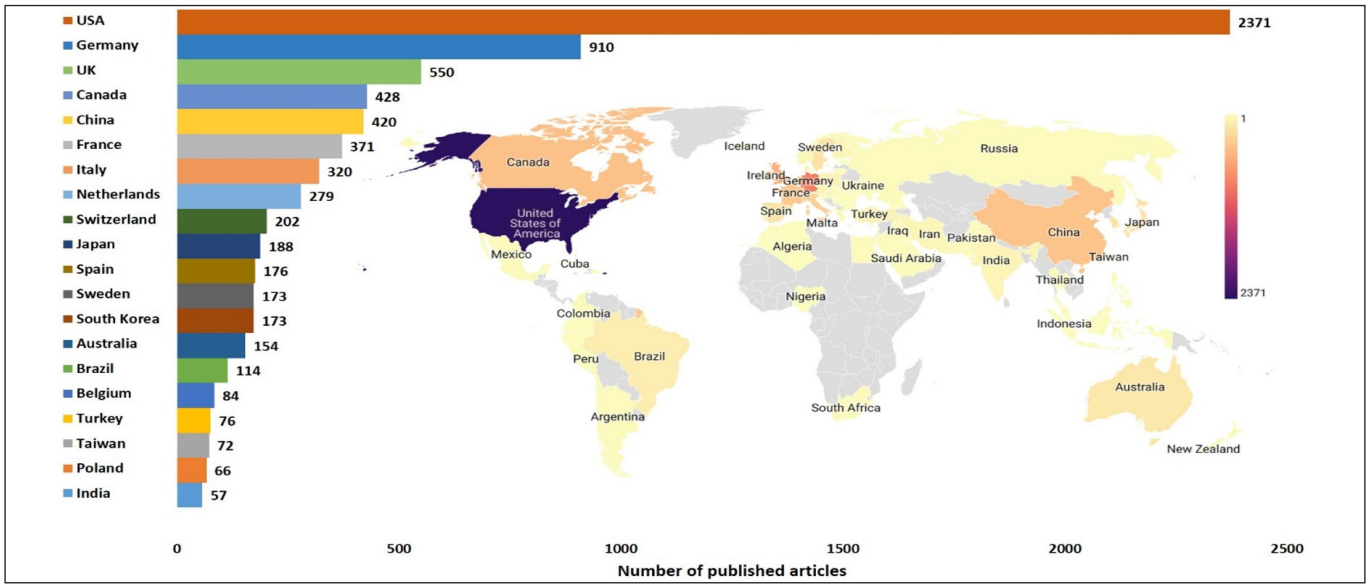

Figure 2. A bar graph showing the top 20 countries with the most published articles on deep brain stimulation (DBS) and a world productivity map showing the distribution of published articles by country.

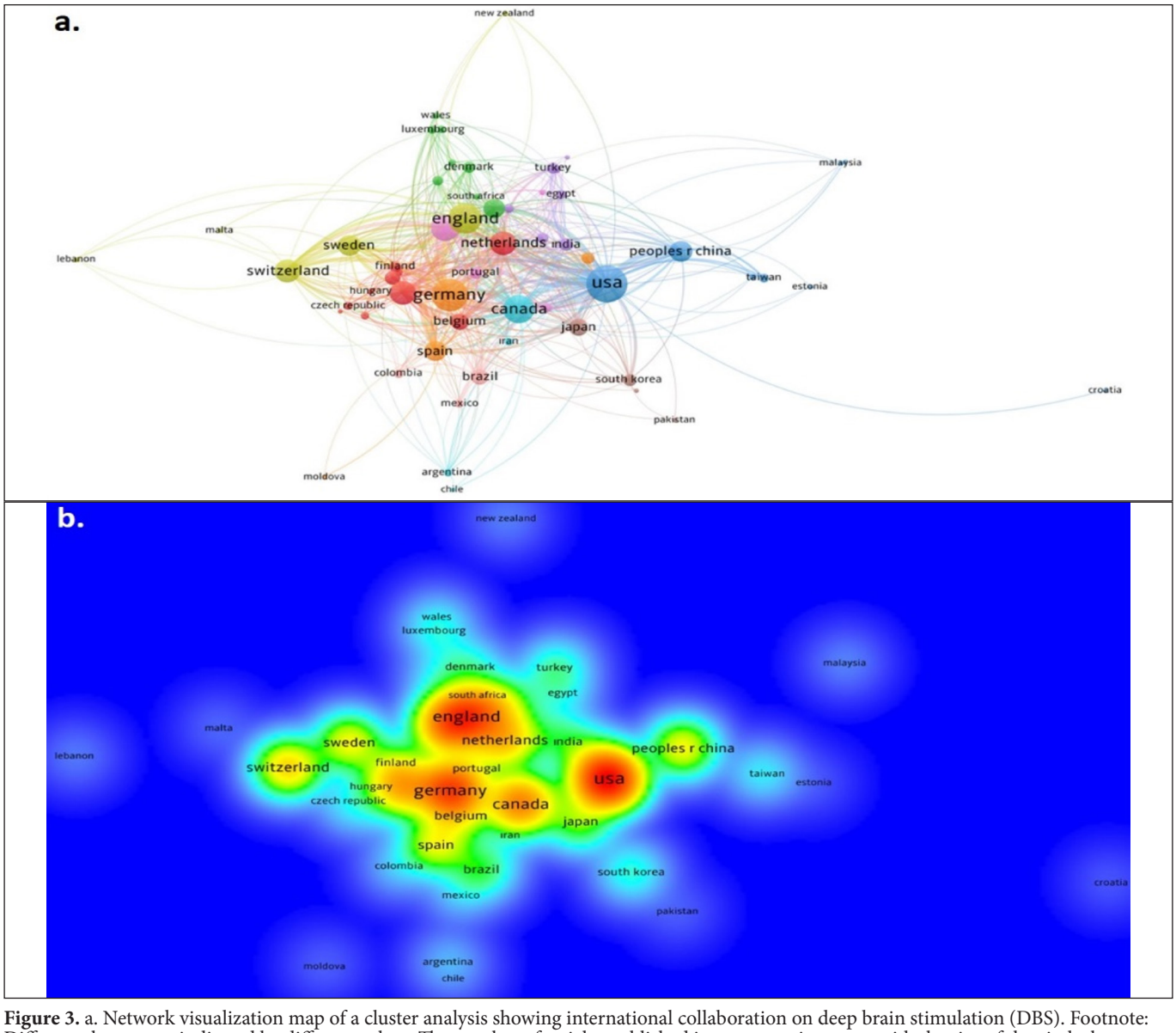

Figure 3. a. Network visualization map of a cluster analysis showing international collaboration on deep brain stimulation (DBS). Footnote: Different clusters are indicated by different colors. The number of articles published in a country increases with the size of the circle. b. A density map displaying the level of international collaboration on DBS among countries. Footnote: The score for the degree of global cooperation goes from blue to red (blue-green-yellow-red).

the scores showing the strength of cooperation were calculated. The cooperation intensity map created based on the calculated cooperation scores is shown in Figure 3.b (Top 15 countries with the highest score for cooperation: USA=994, Germany=701, England=585, Canada=484, France=412, Netherlands=312, Italy=311, Switzerland=298, China=227, Sweden=224, Spain=210, Australia=191, Japan=137, Belgium=126, Brazil=109).

The number of articles published by nations on DBS and their GDP and GDP per capita values were found to be highly statistically correlated (r=0.723, P<0.001; r=0.711, P<0.001, respectively).

Citation Analysis on DBS

The first 25 articles that received the most citations (more than 450 citations) according to the total number of citations out of 5939 articles published on DBS were shared in Table 2 along with the titles, authors, journal names in which they were published, publication years, the total number of citations received by the articles and the average number of citations received per year.

Co-citation Analysis on DBS

There were a total of 74715 publications cited in the references section of all 5939 articles published on DBS.

Table 2. The top 25 most cited articles (more than 450 citations) on deep brain stimulation

No	Article	Author	Journal	PY	TC	AC
1	Deep brain stimulation for treatment-resistant depression	Mayberg HS. et al.	Neuron	2005	2494	138.56
2	A randomized trial of deep-brain stimulation for Parkinson's disease	Deuschl G. et al.	New England Journal of Medicine	2006	1847	108.65
3	Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease.	Obeso JA. et al.	New England Journal of Medicine	2001	1154	52.45
4	Bilateral deep brain stimulation vs best medical therapy for patients with advanced Parkinson disease a randomized controlled trial	Weaver FM. et al.	Jama-Journal of the American Medical Association	2009	1010	72.14
5	Pallidal versus subthalamic deep-brain stimulation for Parkinson's disease	Follett KA. et al.	New England Journal of Medicine	2010	846	65.08
6	Hold your horses: Impulsivity, deep brain stimulation, and medication in parkinsonism	Frank MJ. et al.	Science	2007	752	47
7	Bilateral deep brain stimulation in Parkinson's disease: a multicentre study with 4 years follow-up	Rodriguez-Oroz MC. et al.	Brain	2005	752	41.78
8	Bilateral deep-brain stimulation of the globus pallidus in primary generalized dystonia	Vidailhet M. et al.	New England Journal of Medicine	2005	734	40.78
9	Adaptive deep brain stimulation in advanced Parkinson disease	Little S. et al.	Annals of Neurology	2013	689	68.9
10	Pallidal deep-brain stimulation in primary generalized or segmental dystonia	Kupsch A. et al.	New England Journal of Medicine	2006	659	38.76
11	Subthalamic nucleus deep brain stimulation: Summary and meta-analysis of outcomes	Kleiner-Fisman G. et al.	Movement Disorders	2006	646	38
12	Subcallosal cingulate gyrus deep brain stimulation for treatment-resistant depression	Lozano AM. et al.	Biological Psychiatry	2008	622	41.47
13	Deep brain stimulation to reward circuitry alleviates anhedonia in refractory major depression	Schlaepfer TE. et al.	Neuropsycho-pharmacology	2008	612	40.8
14	Near-infrared deep brain stimulation via upconversion nanoparticle-mediated optogenetics	Chen S. et al.	Science	2018	588	117.6
15	Cellular effects of deep brain stimulation: Model-based analysis of activation and inhibition	McIntyre CC. et al.	Journal of Neurophysiology	2004	549	28.89
16	Deep brain stimulation of the ventral capsule/ventral striatum for treatment-resistant depression	Malone DA. Jr. et al.	Biological Psychiatry	2009	535	38.21
17	Bilateral deep brain stimulation of the pedunculopontine and subthalamic nuclei in severe Parkinson's disease	Stefani A. et al.	Brain	2007	535	33.44
18	Closed-loop deep brain stimulation is superior in ameliorating parkinsonism	Rosin B. et al.	Neuron	2011	507	42.25
19	Nucleus accumbens deep brain stimulation decreases ratings of depression and anxiety in treatment-resistant depression	Bewernick BH. et al.	Biological Psychiatry	2010	507	39
20	Double-blind evaluation of subthalamic nucleus deep brain stimulation in advanced Parkinson's disease	Kumar R. et al.	Neurology	1998	495	19.8
21	Three-year outcomes in deep brain stimulation for highly resistant obsessive-compulsive disorder	Greenberg BD. et al.	Neuropsycho-pharmacology	2006	490	28.82
22	Deep brain stimulation plus best medical therapy versus best medical therapy alone for advanced Parkinson's disease (PD SURG trial): a randomised, open-label trial	Williams A. et al.	Lancet Neurology	2010	485	37.31
23	A phase I trial of deep brain stimulation of memory circuits in Alzheimer's disease	Laxton AW. et al.	Annals of Neurology	2010	482	37.08
24	Deep brain stimulation of the ventral internal capsule/ventral striatum for obsessive-compulsive disorder: worldwide experience	Greenberg BD. et al.	Molecular Psychiatry	2010	466	35.85
25	Transient acute depression induced by high-frequency deep-brain stimulation	Bejjani BP. et al.	New England Journal of Medicine	1999	463	19.29

PY: Publication year, TC: Total citation, AC: Average citations per year

Among these studies, the 7 most influential studies with more than 350 co-citations were Deuschl et al.[4] (Co-Citation, CC=727), Krack et al.[20] (CC: 594), Weaver et al.[9] (435), Obeso et al.[5] (422), Mayberg et al.[12] (401), Limousin et al.[21] (366), and Benabid et al.[22] (352), respectively.

Past and Current Research Trends on DBS

7020 different keywords were used in all 5939 articles published on DBS. 132 different keywords that were used in 15 or more than 15 different articles from these keywords were presented in Table 3. The map created by the keywords as a result of the clustering analysis is presented in Figure 4. The trend network visualization map, which shows the usage of the keywords in the published articles by years, obtained as a result of the keyword analysis carried out to determine past and current research trends, was presented in Figure 5. The citation network visualization map obtained as a result of the citation analysis performed to reveal the most cited topics and showing the citation numbers of the keywords was shown in Figure 6.

Table 3. The 132 most frequently used keywords in different articles on deep brain stimulation

Keywords	NU	Keywords	NU	Keywords	NU	Keywords	NU
deep brain stimulation (or DBS)	4194	treatment resistant depression	46	psychiatry	27	volume of tissue activated	20
parkinson's disease (PD or parkinson disease)	1816	dopamine	44	targeting	27	connectivity	19
subthalamic nucleus deep brain stimulation (or STN or STN-DBS)	926	functional magnetic resonance imaging (or FMRI)	44	machine learning	26	ethics	19
dystonia	348	gait	43	memory	26	major depression	19
globus pallidus (or interna or internus or gpi)	313	pain	43	autonomy	25	obesity	19
essential tremor (or tremor)	454	neurostimulation	42	brain stimulation	25	parkinson&apos	19
movement disorder (s)	186	neuroethics	41	anorexia nervosa	24	secondary dystonia	19
thalamus	183	infection	38	bradykinesia	24	adverse events	18
functional neurosurgery	181	stimulation	36	chronic pain	24	amygdala	18
neuromodulation	167	outcome	35	dementia	24	pallidal stimulation	18
depression	140	safety	35	meige syndrome	24	pallidum	18
obsessive compulsive disorder	130	dysarthria	34	posterior subthalamic area	24	programming	18
basal ganglia	126	electrical stimulation	34	verbal fluency	24	serotonin	18
magnetic resonance imaging (MRI)	122	pedunculopontine nucleus	33	addiction	23	cerebellum	17
epilepsy	117	seizure (s)	33	electrophysiology	23	chorea	17
complication (s)	100	diffusion tensor imaging	32	magnetoencephalography	23	functional connectivity	17
microelectrode recording (s)	100	electrode	32	motor cortex	23	general anesthesia	17
nucleus accumbens	94	levodopa	32	speech	23	side effects	17
quality of life	94	psychosurgery	32	treatment	23	transcranial magnetic stimulation	17
local field potential (s)	89	brain shift	31	fornix	22	adaptive deep brain stimulation	16
tourette's syndrome (or tourette syndrome)	89	hypothalamus	31	medial forebrain bundle	22	anesthesia	16
cognition (or cognitive function)	80	rat	31	non-motor symptoms	22	beta oscillations	16
stereotactic surgery (or neurosurgery)	76	stereotaxy	31	deep brain stimulator	21	cerebral palsy	16
neurosurgery	65	accuracy	30	meta-analysis	20	hemorrhage	16
ventral intermediate nucleus (or VIM)	58	zona incerta	30	multiple sclerosis	20	mood	16
computational model (or modeling)	54	alzheimer's disease	29	neuropathic pain	20	parkinsonism	16
neuropsychology (or neurophysiology)	53	cervical dystonia	29	pallidotomy	20	prefrontal cortex	16
positron emission tomography (or PET)	51	cluster headache	29	sleep	20	anterior nucleus	15
tractography	51	thalamotomy	29	striatum	20	brain	15
hippocampus	49	parkinson&#8217	28	substantia nigra	20	evoked potentials	15
S disease	47	anxiety	27	thalamic stimulation	20	finite element method	15
high frequency stimulation	46	dyskinesia	27	tics	20	schizophrenia	15
surgery	46	freezing of gait	27	ventral striatum	20	self	15

NU: Number of uses

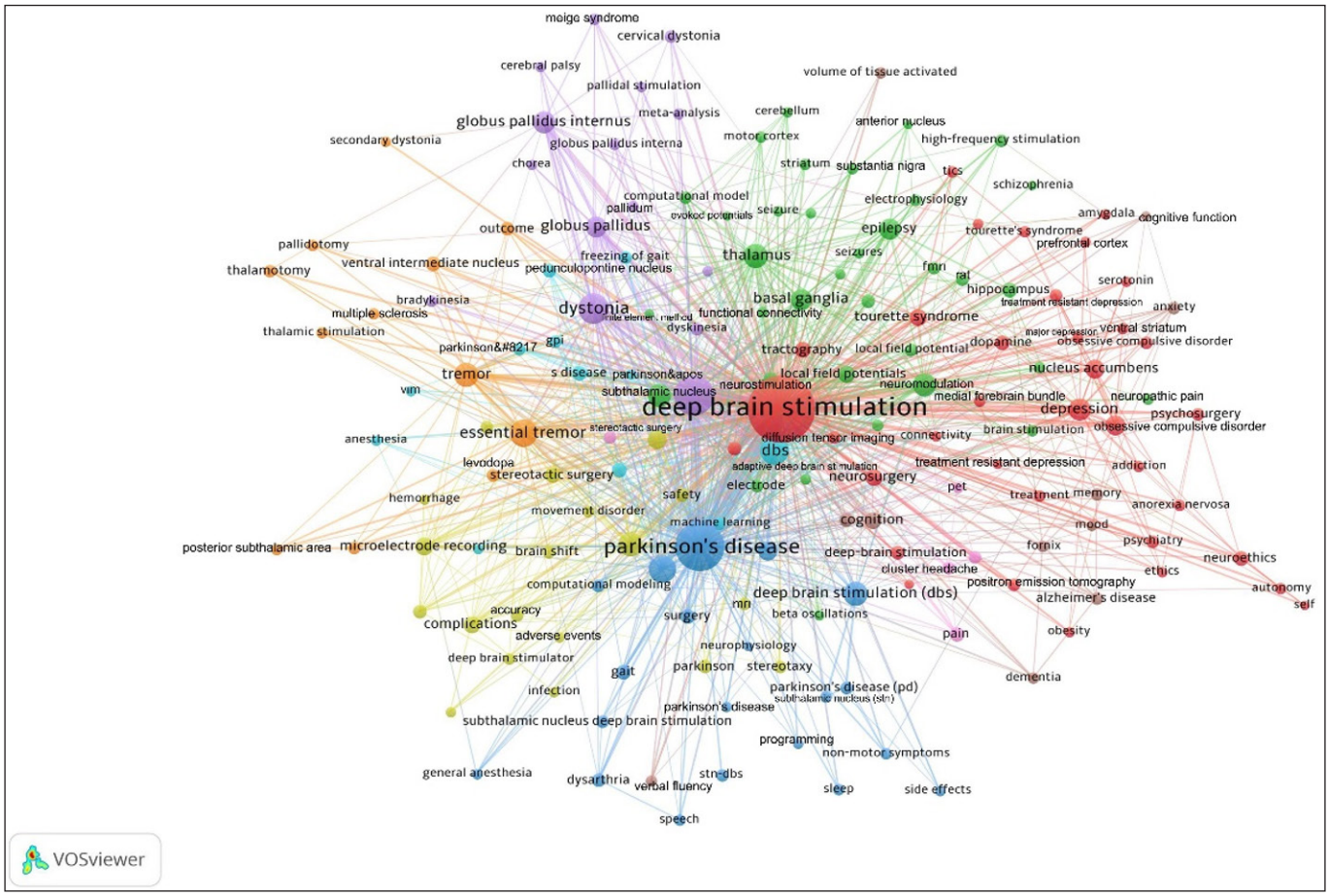

Figure 4. A network visualization map created to show how deep brain stimulation (DBS) topics tend to cluster, based on keyword analysis. Footnote: Different clusters are indicated by different colors. Similar-colored keywords are in the same clusters. The number of keyword uses is indicated by the size of the circle.

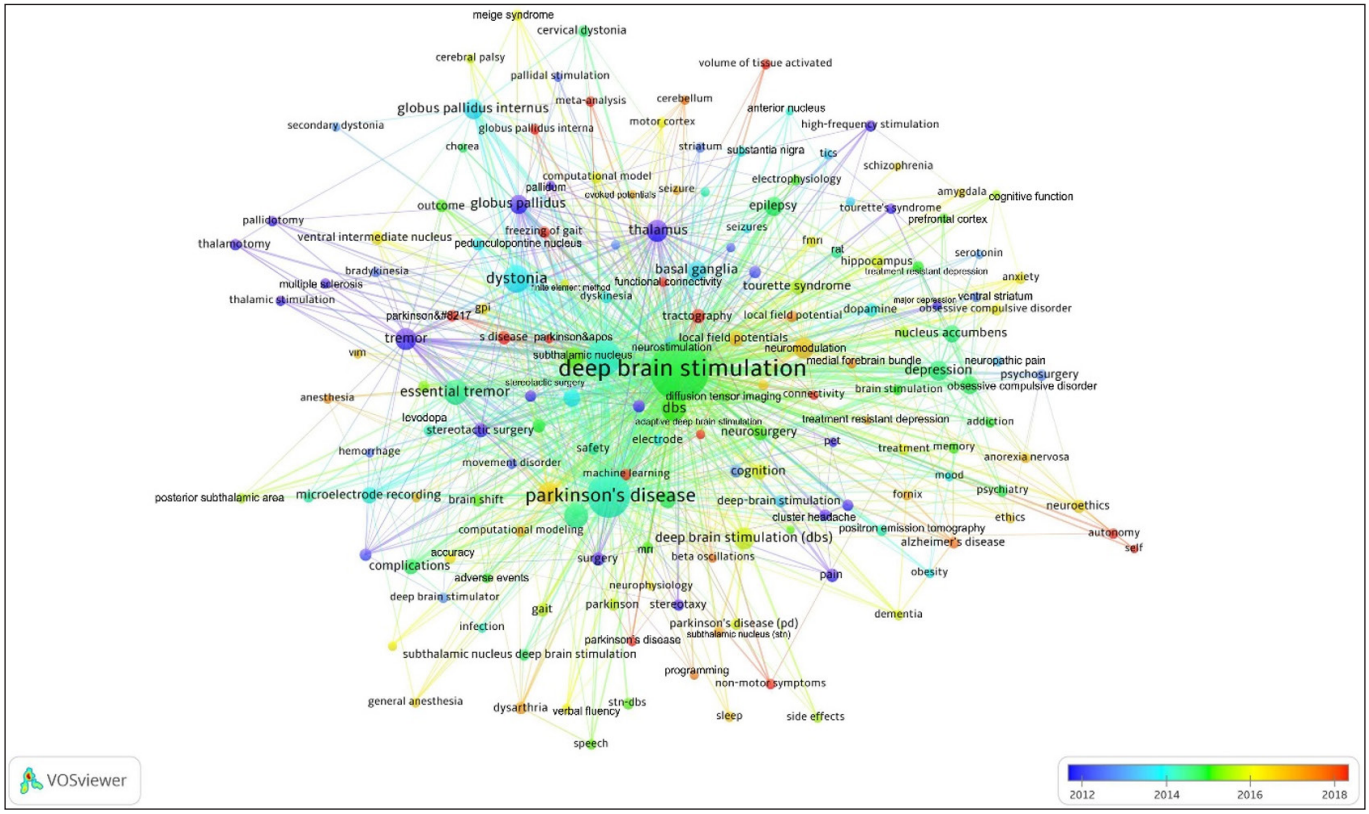

Figure 5. A network visualization map showing past and current trends in deep brain stimulation (DBS) based on keyword analysis. Footnote: The indicator in the figure's lower right corner changes from blue to red (blue-green-yellow-red) as the topics' actuality increases. The number of keyword uses is indicated by the size of the circle.

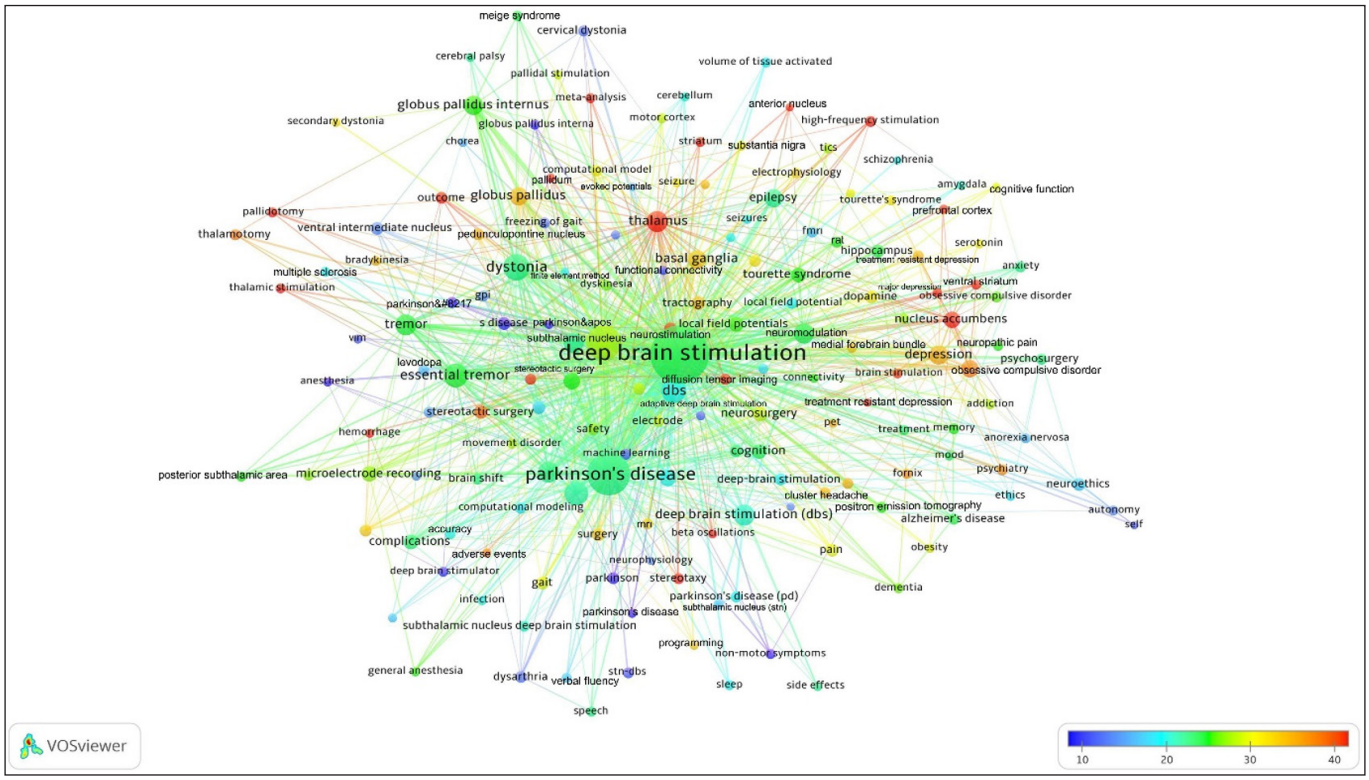

Figure 6. A network visualization map showing citation counts of topics based on keyword analysis in deep brain stimulation (DBS).
Footnote: The indicator in the figure's lower right corner changes from blue to red (blue-green-yellow-red) as the topic receives more citations. The number of keyword uses is indicated by the size of the circle.

DISCUSSION

When the distribution of articles on DBS between 1980 and 2022 was evaluated, there were seen to be 4 different publication trends in the periods of 1980-1998, 1999-2005, 2006-2012, and 2013-2021. A mean of 2 articles per year (range, 1-9) were published between 1980 and 1998. A trend for an increase in the number of articles started in 1999 and mean 59 articles per year (range, 24-86) were published between 1999 and 2005. A second increase trend started in 2006 with mean 218 articles (range, 125-283) published in the period 2006-2012. A third increase was seen to start in 2013, with mean 401 articles (range, 319-544) published between 2013 and 2021. When the 5-year prediction findings were evaluated together with the previous trends, it can be said that from 2022, the increasing trend of scientific productivity on the subject of DBS will continue.

When the article productivity of countries around the world was examined, 17 of the 20 countries (United States of America, Germany, United Kingdom, Canada, France, Italy, Netherlands, Switzerland, Japan, Spain, South Korea, Sweden, Australia, Brazil, Belgium, Taiwan, Poland) contributing the most to literature on DBS were determined to be developed countries and only 3 were developing countries (China, Turkey, India; countries classified as developing but with large economies). A significant correlation at a high level was determined between the number of articles published on the subject of DBS by a country and the GDP and GDP per capita of the country, which showed that the economic size of a country has an impact on the global productivity of articles on DBS. Some previous bibliometric studies in literature on different subjects have also shown significant correlations at moderate and high levels.[13-16] A density map was created based on the total collaboration scores between countries. When this map was interpreted, it was seen that the countries with the most intense cooperation were the USA, Germany, England (in UK), Canada, France, the Netherlands, Italy, Switzerland, China, Sweden, Spain, and Australia. When the common author collaboration was examined, although collaboration was based on geographic proximity in Europe, South America, and the Far East, global collaboration was generally widespread.

The main active journals that contributed the most to the literature on DBS were Stereotactic and Functional Neurosurgery, Movement Disorders, Journal of Neurosurgery, Parkinsonism & Related Disorders, Neuromodulation, Brain Stimulation, World Neurosurgery, Neurosurgery, and Acta Neurochirurgica, respectively. We can state that these journals are more productive for researchers who are preparing to publish on this subject. When the average number of citations per article published by the journals is evaluated (which have published at least 2 articles on DBS), we can say that the most influential journals were the New England

Journal of Medicine (Average number of citations per article=783), Neuron (662), Science (379), Nature Neuroscience (319), Lancet Neurology (246), Archives of General Psychiatry (229), Biological Psychiatry (180), Lancet Psychiatry (167), Neuropsychopharmacology (131), American Journal of Psychiatry (130), Brain (107), Journal of Chemical Neuroanatomy (106), Archives of Neurology (106), Annals of Neurology (97), Nature Medicine (96), and Neurology (95), respectively.

When the total number of citations received by the analysed articles was examined, it was determined that the most influential study with the highest number of citations was Mayberg's et al.[12] study entitled "Deep brain stimulation for treatment-resistant depression" published in Neuron. The second most influential study is Deuschl et al.'s[4] article titled "A randomized trial of deep-brain stimulation for Parkinson's disease" published in the New England Journal of Medicine. The third most effective paper is Obeso et al.'s[5] article entitled "Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease" published in the New England Journal of Medicine. The fourth and fifth most influential studies were Weaver et al.[9] and Follett et al.'s[8] articles.

When the average number of citations per year is evaluated, the most influential study is Mayberg et al.[12] The second most influential article is Chen et al.[23] published in Science, titled "Near-infrared deep brain stimulation via upconversion nanoparticle-mediated optogenetics". The third most influential paper is Deuschl et al.[4] The fourth most influential paper is Weaver et al.[9] The fifth most influential paper is Horn et al.[24] published in Neuroimage, titled "Lead-DBS v2: Towards a comprehensive pipeline for deep brain stimulation imaging".

According to the total co-citation numbers of all analyzed articles, the most influential studies were Deuschl et al. [4], Krack et al.[20], Weaver et al.[9], Obeso et al.[5], Mayberg et al.[12], Limousin et al.[21], and Benabid et al.[22] We can suggest that researchers interested in this topic should first read these most co-cited prominent studies.

According to the cluster analysis findings, it was determined that the subtopics used in the DBS main topic were divided into 10 different clusters. The most studied topics from past to present were parkinson's disease, subthalamic nucleus deep brain stimulation, dystonia, globus pallidus, essential tremor, movement disorders, thalamus, functional neurosurgery, neuromodulation, depression, obsessive compulsive disorder, basal ganglia, magnetic resonance imaging (MRI), epilepsy, complications, microelectrode recording, nucleus accumbens, quality of life, local field potentials and tourette's syndrome.

According to the keyword analysis findings carried out to identify trend topics, the most studied trend topics (used in at least 15 different articles in recent years) in the articles published in recent years were tractography, freezing of gait, Parkinson's disease, Parkinson&#8217, Parkinson#apos, autonomy, self, machine learning, non-motor symptoms, functional connectivity, globus pallidus interna, meta-analysis, volume of tissue activated, adaptive deep brain stimulation, beta oscillations, medial forebrain bundle, and local field potential. Also, other trending topics (used in at least 10 different articles in recent years) were Optogenetics, pediatric, frameless, closed-loop DBS, refractory epilepsy, satellite broadcasting, asleep DBS, optimization, biomarker, directional Leeds, nucleus bassals of meynert, personality, identity, authenticity, and anterior nucleus of thalamus. It was also determined that thalamus, thalamus, nucleus accumbens, anterior nucleus, high-frequency stimulation, thalamic stimulation, stereotaxy, outcome, pallidotomy, pallidum, beta oscillations, striatum, ventral striatum, prefrontal cortex, major depression, treatment resistant depression, diffusion tensor imaging, hemorrhage and stereotactic neurosurgery were the most cited keywords among the keywords used in the articles published on DBS from past to present.

From the literature scan performed for this study, there was seen to be no comprehensive bibliometric study on the general subject of DBS. Hu et al.[25] discussed the bibliometric analysis of the 100 most cited articles. Listick et al.[11] evaluated the bibliometric analysis of the 100 most cited articles on DBS treatment of dystonia, and Mishra et al.[26] conducted bibliometric analyses of the 84 most cited articles on the subject of Local Field Potentials in DBS. In the current study, 5939 articles were analysed, so there can be said to be an advantage over other studies in respect of the scope and time period. Another important advantage is the inclusion of different bibliometric approaches such as trend keyword analyses, clusters, correlations, and international collaboration analyses in addition to citation analyses.

A limitation of this study could be considered to be that only the WoS was used in the literature scan. However, it has been emphasized in several studies that the PubMed database is not preferred in bibliometric analyses as citation and co-citation analyses cannot be performed on this.[13-16] In the Scopus database, some low-impact journals are indexed.[14,15] Therefore, compared to other databases, the articles in the WoS are indexed in higher impact journals (the majority in SCI-expanded).[27] In other bibliometric studies in the literature, the WoS has been generally preferred.[13-16,27]

CONCLUSION

We presented a statistical analysis of 5939 articles in this comprehensive research we conducted on DBS, which has an exponential increase in the number of articles in recent years. When the findings of the analysis carried out to determine the trend topics are examined, the primary topics that have been studied more in recent years are tractography, freezing of gait, Parkinson's disease, Parkinson&#8217, Parkinson#apos, autonomy, self, machine learning, non-motor symptoms, functional connectivity, globus pallidus interna, meta-analysis, volume of tissue activated, adaptive deep brain stimulation, beta oscillations, medial forebrain bundle, and local field potential. It can be said that the trending secondary topics in recent years are optogenetics, pediatric, frameless, closed-loop DBS, refractory epilepsy, satellite broadcasting, asleep DBS, optimization, biomarker, directional Leeds, nucleus bassals of meynert, personality, identity, authenticity, and anterior nucleus of thalamus. We have identified the research leadership of Western countries with large economies (especially the USA, European countries and Canada) and China on DBS. Although there are important international collaborations globally, we think that research on DBS in underdeveloped countries should also be encouraged. These bibliometric analyses may contribute to the emergence of new ideas for future studies.

ETHICAL DECLARATIONS

Ethics Committee Approval: This article does not contain any studies with human participants or animals performed by any of the author. For this type of study ethics committee approval is not required.

Informed consent: For this type of study formal consent is not required.

Referee Evaluation Process: Externally peer reviewed.

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