

RESEARCH ARTICLE

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Diffusion tensor imaging from past to present: A bibliometric analysis with trending topics and global productivity during 1980–2022

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Abstract

Diffusion tensor imaging (DTI) provides increasing opportunities for clinicians. As bibliometric studies define trends of novel modality applications, this study on DTI analyzed global productivity, most prolific institutions, and research areas. Articles obtained from the Web of Science (WoS) database were analyzed with the VOSviewer program, biblioshiny library in the R studio software bibliometrix package, exponential smoothing estimator, and with the SPSS (Version: 22.0) statistical software. In descending order, the United States, China, and Germany were the top 3 countries publishing DTI research. In descending order, the top 3 most productive institutions were California, Harvard and Johns Hopkins University. Trend topics include traumatic brain injury, tract-based spatial statistics, fractional anisotropy, prognosis, machine learning, autism, white matter integrity and microstructure and Parkinson's disease. According to the estimations, 345 DTI articles will be published in 2025 (95% CI: 254–437). This study indicates the ever-growing employment of DTI in clinical and basic sciences.

KEYWORDS

bibliometric analysis, citation analysis, diffusion tensor imaging, research trends, scientometric analysis

1 | INTRODUCTION

Diffusion tensor imaging (DTI) is a specialized technique that uses diffusion-weighted imaging (DWI) modality of magnetic resonance imaging (MRI). DTI is a variation of DWI that uses a tissue water diffusion rate for image generation, investigating the fiber structure of various regions of the human body, such as the white matter of the brain or muscle fibers of the heart. Yet, unlike DWI, instead of just one numerical value for each voxel, a diffusion tensor (3×3 matrix) is calculated, allowing anisotropic diffusion to be investigated.^{1,2} DTI provides unique microstructural, cellular, and macromolecular information that is heterogenous but oriented towards the

presence of spatiality.³ The success of DTI is due to its ability to probe the tissue structure of molecules on a microscopic scale during their random, diffusion-guided displacements, well beyond standard image resolution. Diffusion is mostly measured in terms of fractional anisotropy (FA), mean spread (MD), apparent diffusion coefficient (ADC), radial spread (RD), and axial spread (AD).⁴ The most common indicator, FA, is generally interpreted as an indicator of white matter integrity and roughly indicates how much water in the micro- and macro-structure undergoes anisotropic diffusion.⁴ DTI allows the reconstruction, visualization, and evaluation of the specific attributes of white matter. Advances in DWI over the past 20 years have led to the use of DTI

to characterize the neural structural integrity further and monitor neuronal pathways in the brain and spine, leading to many applications that increase the diagnostic potential of MRI.⁵ DTI has been successfully used to study neurological diseases and mental disorders, including stroke, brain tumors, multiple sclerosis, schizophrenia, dyslexia, autism, and neurogenetic conditions, besides providing valuable information on changes in the white matter microstructure during neurodevelopment and aging.^{6,7} New DTI and DTI-derived tractography (DDT) applications have shown surgeons that preoperative mapping of functionally relevant cortical regions and white matter tracts (WMT) is critical during surgical planning to reduce post-operative problems.⁸

Bibliometric analysis is a new type of quantitative study widely preferred in recent years, using various statistical approaches to analyze large amounts of scientific data.^{9,10} Unlike the qualitative literature reviews that scholars' bias can influence, meta-analyses and bibliometric studies are performed with quantitative techniques reducing such bias. Meta-analyses summarize tentative evidence by analyzing the effect strengths and relationships between variables. In a different approach, bibliometric analysis summarizes and maps a field's intellectual structure by examining relationships among versatile research components. Well-performed bibliometric studies can provide a significant establishment for advancing a field uniquely, providing an eminent overview for basic and clinical scientists. Thus, bibliometric analyses identify critical points for future research by providing comprehensive structured information about a research subject.^{11,12} Bibliometric methods are helpful in many aspects, including, yet not limited to, identifying trending topics in a specific field, tracking research history, and predicting future directions of investigation. On the basis of this background, the primary purpose of the current bibliometric study is to analyze global and country-based research productivity, international cooperation, the latest research trends, and the most prolific institutions and authors regarding DTI.

2 | MATERIALS AND METHODS

2.1 | Article retrieval, inclusion and exclusion criteria

The retrieval of the DTI articles comprised the WoS (Web of Science Core Collection by Clarivate Analytics) database analysis (last accession: May 1, 2023). The article inclusion period was between 1980 and 2022. The reason for limiting literature retrieval until 2022 is the ever-increasing trend of online and early access publications,

TABLE 1 The search strategy to retrieve articles relevant to the study objective.

Parameters	Search options
Search terms	(Title = "diffusion tensor") OR (Title = "DTI" AND Topic = "diffusion tensor")
Database used	Web of Science (WoS)
Search period	1980–2022
Inclusion criteria	The study included all full-text original articles regarding medical applications of the DTI, obtained with the utilized search terms.
Exclusion criteria	Review articles, meeting abstracts, and proceeding papers were excluded from the study. Non-medical studies on DTI (i.e., geophysics, thermodynamics, metallurgy) were also excluded after reading all the abstracts of the retrieved articles.

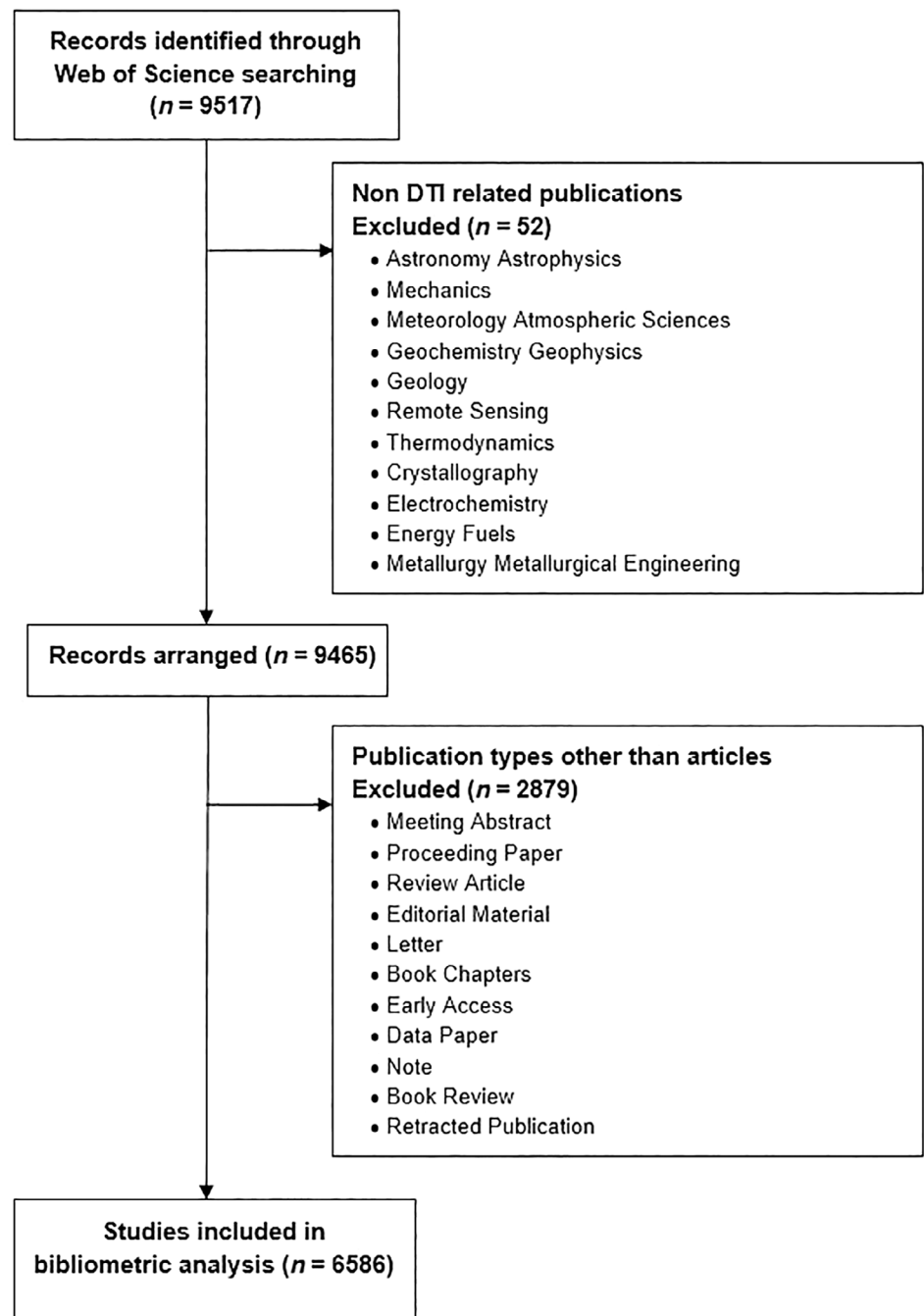
Abbreviation: DTI, Diffusion tensor imaging.

for which the information regarding the publication year mainly changes, sometimes much later than assignments to DOI (Digital Object Identifier) numbers. Thus, limiting the research until 2022 aimed to avoid blurring results and to be more precise. As shown in Table 1, researchers can confirm the study's replicability by analyzing the WoS database with the following search items: [(Title = "diffusion tensor")] OR [(Title = "DTI" AND Topic = "diffusion tensor")] and by referring to the Figure 1. This first search yielded 9517 articles. The other inclusion and exclusion criteria were the medical and full-text original studies and non-medical DTI applications (i.e., geophysics, thermodynamics, metallurgy) or other types of sources such as abstracts and reviews, respectively. After excluding 52 non-medical DTI studies, the re-arranged 9465 studies were subjected to another exclusion of 2879 sources, such as reviews, as explained. At last, 6586 original articles remained, which fulfilled all the inclusion and exclusion criteria investigated subsequently with bibliometric analyses. The reader can refer to Figure 1 to find the details of the exclusion criteria.

2.2 | Statistical and bibliometric analysis

Statistical analyses were performed with the SPSS (version: 22.0, SPSS Inc., Chicago, IL, USA) software. The number of DTI publications in the coming years was predicted by utilizing past article numbers and assessments with the Exponential Smoothing estimator of the Microsoft Excel program. The color density world map depicting the productivity of the DTI articles was drawn using

FIGURE 1 The flowchart of the article retrieval algorithm. DTI, diffusion tensor imaging.



the open-access website <https://app.datawrapper.de>. The Microsoft PowerPoint program was employed to draw the color-density bar graphs. The Kolmogorov–Smirnov test and histogram graphs were used to determine the normal distribution of the data before the correlation analyses. Then, the Spearman correlation test was performed to analyze the correlations between the numerical data obtained from the World Bank and the WoS database.¹³ Results with *p*-values lower than 0.05 were accepted as significant. The bibliometric assessments, including citation, trending topic, and international relations analyses, were performed with the VOSviewer (Version 1.6.18, Leiden University)

package program.¹⁴ This program enables the creation of networks based on citation, co-authorship, and co-occurrence data retrieved from the WoS database. It employs advanced techniques for the network layout and clustering analyses and fine-tunes the results obtained according to different parameters. By fractional counting, the Vosviewer program reduces the influence of publications with many authors, citations, or references, and could perform data cleaning using thesaurus files. Trend keyword analyses on different time periods were made with the biblioshiny interface (<http://www.bibliometrix.org/>) in the bibliometrix library in R Studio-Tool.

3 | RESULTS

3.1 | Numbers, types, languages, and indexing information of the retrieved articles

As mentioned, 6586 (69.6%) of the 9517 articles retrieved with the initial WoS analysis were original full-text articles. After excluding the non-medical DTI studies, the remaining 9465 publications included meeting abstracts (1590, 16.8%), proceeding papers (839, 8.9%), reviews (304, 3.2%), letters (101, 1.1%), and others (i.e., book chapters, editorials). The subsequent exclusion of such 2879 studies meant that the remaining 6538 studies were subjected to bibliometric evaluations. Among these, 99.3% were in English, and the remainder were in other languages, including German ($n = 13$), French (12), Spanish (9), Czech (4), Chinese (3), Turkish (3), Korean (2), Polish (1), and Russian (1). Most articles were indexed in the Science Citation Index-Expanded (94.4%, $n = 6214$), and a minority in the Emerging Sources Citation Index (4.4%, $n = 291$). Only 1.2% of the articles were included in the Social Sciences Citation Index.

3.2 | Prominent research areas in diffusion tensor imaging

The top 15 research areas with the highest number of articles published on DTI included studies on radiology/

medical imaging and nuclear medicine (2577, 39.1%), clinical neurology (1800, 27.3%), neurosciences (1788, 27.1%), neuroimaging (1157, 17.5%), psychiatry (447, 6.7%), surgery (405, 6.1%), multidisciplinary sciences (288, 4.3%), pediatrics, interdisciplinary engineering, 2.1%, spectroscopy (138, 2%), biophysics (112, 1.7%), oncology (106, 1.6%), internal medicine (105, 1.5%), and rehabilitation (101, 1.5%).

3.3 | Past and future trends regarding the number of DTI articles

Figure 2 shows the year distribution of the DTI articles in a line graph, including the article numbers published in the past and predicted to be published in the coming years, considering a seasonal correction of the exponential smoothing estimator. According to the distribution of DTI articles between 1980 and 2022, three different publication trends emerged: 1980–1997, 1998–2016, and 2017–2022. An increasing trend in DTI articles started in 1987, with an average of 234 articles (min–max: 11–439) published until 2016. The publication trend decreased in 2017, with an average of 349 articles (min–max: 309–384) published until 2022. The predicted outcome obtained with the smoothing estimator is a linear increase in the DTI research trend regarding the analyses of the three-year forecast findings for 2023 and beyond. According to the Exponential Smoothing estimator, the estimated number of DTI articles will be

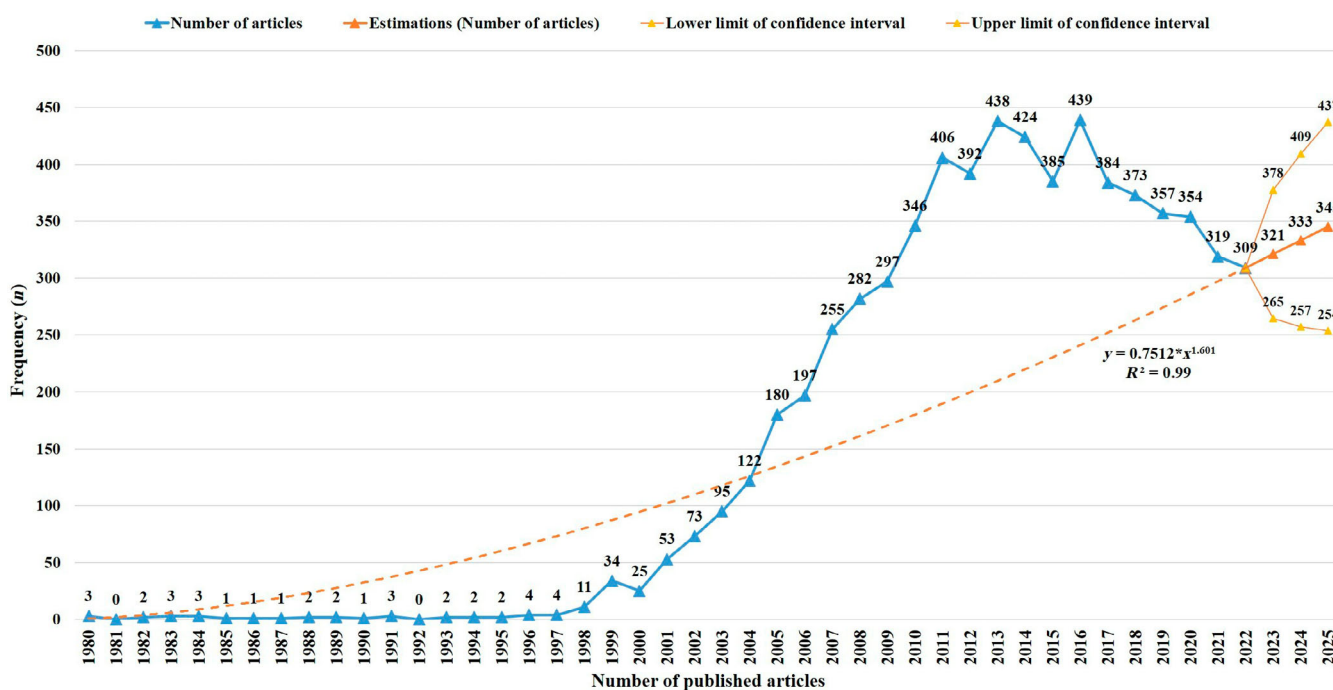


FIGURE 2 Line chart showing the distribution of articles published on diffusion tensor imaging by years between 1980 and 2022 and a forecast of the number of articles that may be issued by 2025.

321 in 2023 (95% confidence interval [CI]: 265–378) and 345 in 2025 (95% CI: 254–437).

3.4 | Prominent institutions in DTI according to the publication numbers

The prominent institutions that published more than 100 articles on DTI are The University of California (297), Harvard University (296), Johns Hopkins University (231), University of London (211), University of Texas (193), Yeungnam University (183), Udice French Research Universities (167), National Institutes of Health NIH USA (137), Institut National de la Sante et de la Recherche Medicale Inserm (125), Brigham and Women's Hospital (120), Massachusetts General Hospital (113), University of Pennsylvania (108), Capital Medical University (104), Stanford University (103), and Centre National de la Recherche Scientifique.

3.5 | Featured journals on DTI regarding the publication numbers and citations

This investigation revealed that 1944 journals published 6508 DTI articles in the analyzed study period. Table 2 demonstrates the ranking of the first 43 journals with the highest contribution to DTI research ranked according to the publication numbers of 30 or above. It also includes data on the number of total and average citations per article. The first five journals that stood out in terms of publication numbers on DTI were Neuroimage, American Journal of Neuroradiology, Journal of Magnetic Resonance Imaging, Magnetic Resonance in Medicine, and Magnetic Resonance Imaging. Table 2 provides all relevant data, so the remaining journals are not repeated here. According to the average number of citations per article, the first five journals that have the most impact are the Journal of Magnetic Resonance Series B (2044), Biophysical Journal (1327), Neuron (572), Computer Methods and Programs in Biomedicine (287), Cortex (220).

TABLE 2 The ranking of the 43 scientific journals publishing the highest numbers of diffusion tensor imaging articles.

Journals	NA	NC	AC	Journals	NA	NC	AC
Neuroimage	337	34 280	102	Acta Radiologica	45	658	15
American Journal of Neuroradiology	236	15 496	66	Frontiers in Neurology	44	294	7
Journal of Magnetic Resonance Imaging	202	7513	37	Journal of Neurology Neurosurgery and Psychiatry	43	4570	106
Magnetic Resonance in Medicine	197	17 928	91	Neuroradiology Journal	43	322	7
Magnetic Resonance Imaging	161	4291	27	IEEE Transactions on Medical Imaging	42	2460	59
Plos One	154	4128	27	Journal of Neurology	41	1158	28
Neuroradiology	123	3728	30	Brain Imaging and Behavior	40	909	23
Human Brain Mapping	95	6496	68	Neurology	40	5783	145
NMR in Biomedicine	93	2914	31	Cerebral Cortex	39	6015	154
European Radiology	87	2745	32	Egyptian Journal of Radiology and Nuclear Medicine	39	96	2
Radiology	83	8829	106	Neurosurgery	39	2112	54
Psychiatry Research-Neuroimaging	76	3549	47	Pediatric Radiology	39	823	21
Neuroimage-Clinical	72	1749	24	Journal of Alzheimers Disease	36	1328	37
Scientific Reports	69	1069	15	Journal of Computer Assisted Tomography	36	605	17
European Journal of Radiology	64	1632	26	Schizophrenia Research	36	2310	64
Journal of Neuroimaging	62	1312	21	Neuroreport	34	1901	56
Journal of Neurotrauma	61	3510	58	Brain Research	33	1633	49
Journal of Neurosurgery	60	2904	48	Neurobiology of Aging	32	3593	112
Neural Regeneration Research	56	253	5	Frontiers in Aging Neuroscience	31	329	11
Neuroscience Letters	56	2078	37	British Journal of Radiology	30	471	16
World Neurosurgery	49	738	15	Journal of the Neurological Sciences	30	765	26
Frontiers in Neuroscience	46	400	9				

Abbreviations: AC, average citation per article; NA, number of articles; NC, number of total citations.

3.6 | Countries most prolific in publishing DTI articles and international collaborations

Figure 3 contains a bar graph depicting the first 18 countries that published over 100 DTI articles and a world map colored according to the intensity of country-based academic contributions. Figure 4 includes a network visualization map demonstrating the clustering of countries in research among 50 that have published at least 5 DTI articles equal to 5 co-occurrences as evaluated by the Vosviewer program based on co-authorship. The top 10 countries that stand out by academic contributions to DTI are the United States (2467, 37.5%), China (1018, 15.5%), Germany (592, 9%), United Kingdom (566, 8.6%), South Korea (427, 6.5%), Japan (418, 6.3%), Canada (298, 4.5%), Italy (298, 4.5%), and France (273, 4.1%). Publication numbers of the remaining countries are not given to avoid redundancy. An analysis of international cooperation among 78 countries that published DTI articles revealed scores showing the collaboration strength. According to these scores, the top 15 countries with the highest collaboration included the United States (1250), United Kingdom (497), Germany (464), China (330), Netherlands (298), Canada (268), Switzerland (247), Italy (244), France (221), Australia (183), Sweden (128), South Korea (121), Belgium (117), Spain (113), and Japan (95). The number of DTI articles correlated highly

significantly with the countries' Gross Domestic Product (GDP) and GDP per capita, which are the leading economic size indicators ($r = 0.737$, $p < 0.001$; $r = 0.719$, $p < 0.001$, respectively).

3.7 | Authors most prolific in publishing DTI studies

The prominent authors who contributed 50 articles or more to the literature on DTI were Jang SH (174), Mori S (94), Filippi M (68), Hasan KM (65), Westin CF (56), Aoki S (55), Kim SH (53), Leemans A (52), and Gupta RK (51), respectively.

3.8 | Citation and co-citation analyses regarding DTI

Table 3 provides data on 30 articles with the highest impact, ranked according to the total citation numbers above 500 for all. It includes additional information on the names of the first authors and journals publishing these studies, as well as the time of publication and citations per year. Bassler and colleagues' (1994) article published in the *Biophysical Journal* achieved the highest citation, followed again by the co-authored study of Bassler and Pierpaoli (1996), published in the *Journal of*

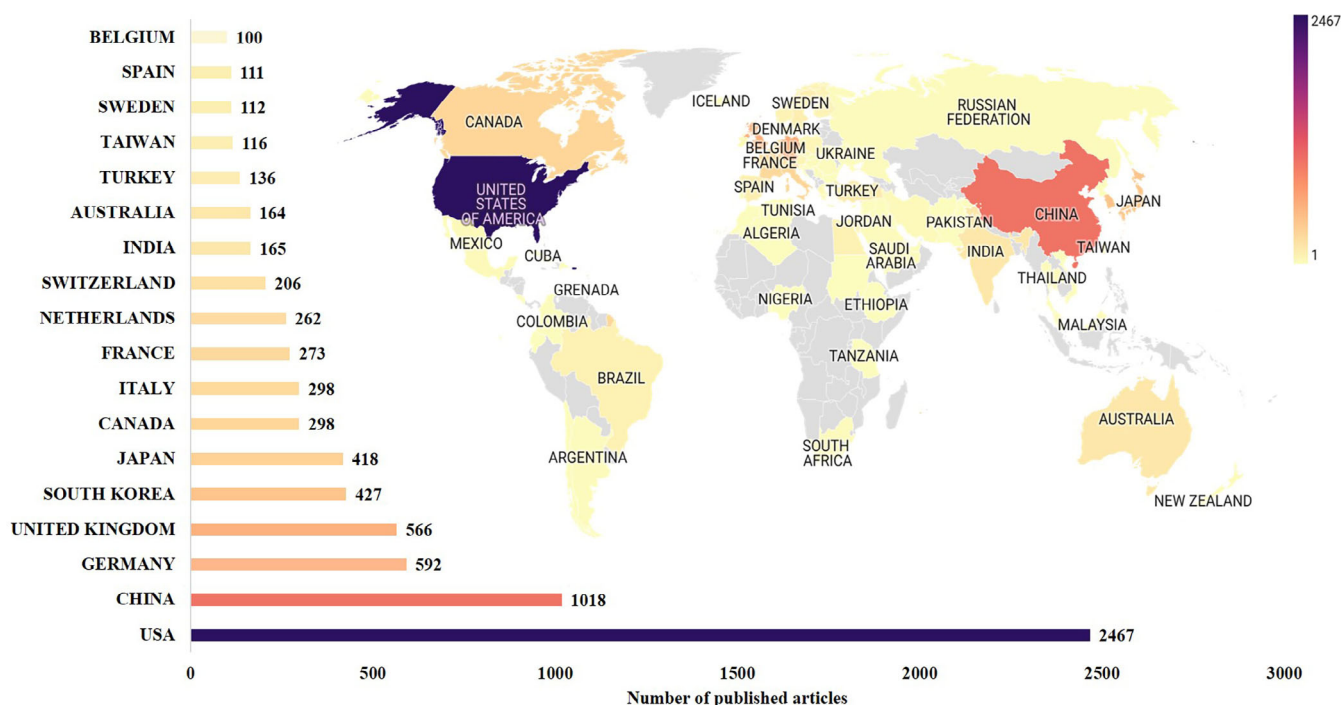


FIGURE 3 Bar chart showing the top 18 countries that have made more than 100 academic contributions to the literature on diffusion tensor imaging, and a world map showing the density of the number of articles published by countries according to colors.

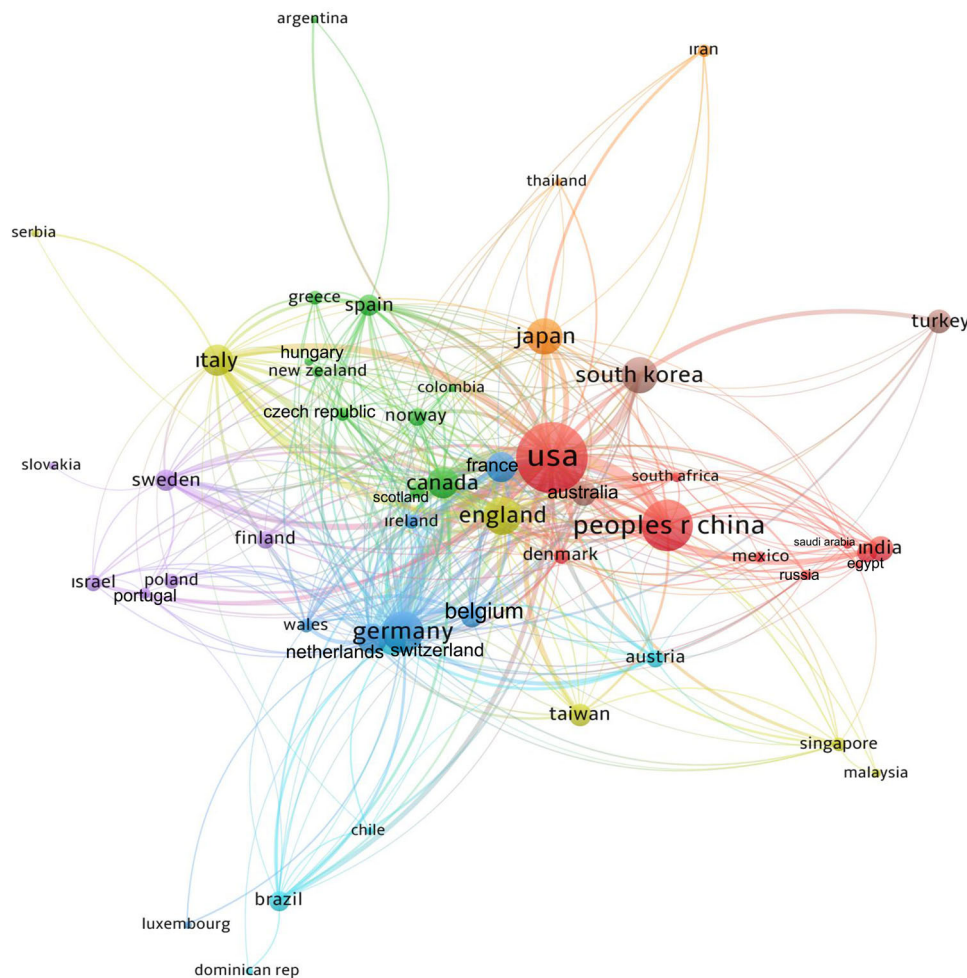


FIGURE 4 Network visualization map showing international cooperation on diffusion tensor imaging (DTI). International cooperation analysis was conducted among 50 countries that published at least five articles on DTI. The thickness of the lines between countries shows the strength of cooperation. The size of the circles increases as the number of articles in the country increases. The colors of the circles indicate clustering. Countries with the same color are in the same cluster and have academic cooperation on DTI. Cluster 1 (red): Denmark, Egypt, India, Mexico, China, Romania, Russia, Saudi Arabia, South Africa, United States. Cluster 2 (green): Argentina, Canada, Colombia, Czech Republic, Greece, Hungary, New Zealand, Norway, Scotland in UK, Spain. Cluster 3 (blue): Belgium, France, Germany, Ireland, Netherlands, Wales in UK. Cluster 4 (yellow): England in UK, Italy, Malaysia, Serbia, Singapore, Taiwan. Cluster 5 (purple): Finland, Israel, Poland, Portugal, Slovakia, Sweden. Cluster 6 (turquoise): Austria, Brazil, Chile, Dominican republic, Switzerland. Cluster 7 (Orange): Iran, Japan, Thailand. Cluster 8 (Brown): Australia, South Korea, Turkey.

Magnetic Resonance Series B. The third most influential study also belonged to Bassar and colleagues (1994) in the same journal, where they achieved the second-highest citation scores. The fourth and fifth leading articles belonged to the teams of Pierpaoli (1996) and Andersson (2003), published in *Radiology* and *Neuroimage* journals, respectively. Readers may refer to Table 3 for the remaining articles with the highest impact.

Regarding the co-citations, 6586 DTI articles cited 106 049 publications in their references. Among these publications, the 10 most influential studies with more than 600 co-citations belonged to Bassar and Pierpaoli (1996) (Number of co-citations, NC = 1036), Bassar et al. (1994) (NC = 952), Smith et al. (2006) (NC = 783), Mori

et al. (1999) (NC = 773), Beaulieu (2002) (NC = 760), Bassar et al. (1994) (NC = 738), Le Bihan et al. (2001) (NC = 691), Pierpaoli et al. (1996) (NC = 679), Pierpaoli and Bassar (1996) (NC = 673), and Smith et al. (2004) (NC = 640) (1, 3, 16–23).

3.9 | Past and current trends regarding the research topics in DTI assessed according to keywords

A total of 8522 different keywords were used in all 6586 articles published on DTI. Among these, 142 keywords used in 15 or more other articles are presented in Table 4.

TABLE 3 The ranking of the 30 most-cited diffusion tensor imaging (DTI) articles.

No	Article	Author	Journal	PY	TC	AC
1	MR diffusion tensor spectroscopy and imaging	Basser PJ et al.	Biophysical Journal	1994	3915	130.5
2	Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI	Basser PJ and Pierpaoli C	Journal of Magnetic Resonance Series B	1996	3413	121.89
3	Estimation of the effective self-diffusion tensor from the NMR spin-echo	Basser PJ et al.	Journal of Magnetic Resonance Series B	1994	2691	89.7
4	Diffusion tensor MR imaging of the human brain	Pierpaoli C et al.	Radiology	1996	2017	72.04
5	How to correct susceptibility distortions in spin-echo echo-planar images: application to diffusion tensor imaging	Andersson JLR et al.	Neuroimage	2003	1677	79.86
6	Diffusion tensor imaging detects and differentiates axon and myelin degeneration in mouse optic nerve after retinal ischemia	Song SK et al.	Neuroimage	2003	1421	67.67
7	Stereotaxic white matter atlas based on diffusion tensor imaging in an ICBM template	Mori S et al.	Neuroimage	2008	1233	77.06
8	A diffusion tensor imaging tractography atlas for virtual in vivo dissections	Catani M and Thiebaut de Schotten M	Cortex	2008	1155	72.19
9	The B-matrix must be rotated when correcting for subject motion in DTI data	Leemans A and Jones DK	Magnetic Resonance in Medicine	2009	990	66
10	Topography of the human corpus callosum revisited—Comprehensive fiber tractography using diffusion tensor magnetic resonance imaging	Hofer S and Frahm J	Neuroimage	2006	879	48.83
11	DtiStudio: Resource program for diffusion tensor computation and fiber bundle tracking	Jiang HY et al.	Computer Methods and Programs in Biomedicine	2006	840	46.67
12	Mapping anatomical connectivity patterns of human cerebral cortex using in vivo diffusion tensor imaging tractography	Gong G et al.	Cerebral Cortex	2009	821	54.73
13	White matter integrity and cognition in chronic traumatic brain injury: a diffusion tensor imaging study	Kraus MF et al.	Brain	2007	723	42.53
14	Log-euclidean metrics for fast and simple calculus on diffusion tensors	Arsigny V et al.	Magnetic Resonance in Medicine	2006	716	39.78
15	Diffusion tensor imaging of white matter tract evolution over the lifespan	Lebel C et al.	Neuroimage	2012	709	59.08
16	Color schemes to represent the orientation of anisotropic tissues from diffusion tensor data: Application to white matter fiber tract mapping in the human brain	Pajevic S and Pierpaoli C	Magnetic Resonance in Medicine	1999	628	25.12

TABLE 3 (Continued)

No	Article	Author	Journal	PY	TC	AC
17	Diffusion tensor imaging and beyond	Tournier JD et al.	Magnetic Resonance in Medicine	2011	627	48.23
18	White matter development during childhood and adolescence: A cross-sectional diffusion tensor imaging study	Barnea-Goraly N et al.	Cerebral Cortex	2005	620	32.63
19	Age-related alterations in white matter microstructure measured by diffusion tensor imaging	Salat DH et al.	Neurobiology of Aging	2005	619	32.58
20	The effect of gradient sampling schemes on measures derived from diffusion tensor MRI: A Monte Carlo study	Jones DK	Magnetic Resonance in Medicine	2004	604	30.2
21	Processing and visualization for diffusion tensor MRI	Westin CF et al.	Medical Image Analysis	2002	601	27.32
22	Microstructure of temporo-parietal white matter as a basis for reading ability: Evidence from diffusion tensor magnetic resonance imaging	Klingberg T et al.	Neuron	2000	572	23.83
23	Diffusion tensor MR imaging in diffuse axonal injury	Arfanakis K et al.	American Journal of Neuroradiology	2002	565	25.68
24	Microstructural development of human newborn cerebral white matter assessed in vivo by diffusion tensor magnetic resonance imaging	Huppi PS et al.	Pediatric Research	1998	542	20.85
25	Life-span changes of the human brain white matter: diffusion tensor imaging (DTI) and volumetry	Westlye LT et al.	Cerebral Cortex	2010	533	38.07
26	White matter structure in autism: Preliminary evidence from diffusion tensor imaging	Barnea-Goraly N et al.	Biological Psychiatry	2004	532	26.6
27	Normal brain in human newborns: Apparent diffusion coefficient and diffusion anisotropy measured by using diffusion tensor MR imaging	Neil JJ et al.	Radiology	1998	518	19.92
28	Analysis of partial volume effects in diffusion-tensor MRI	Alexander AL et al.	Magnetic Resonance in Medicine	2001	516	22.43
29	Diffusion tensor imaging of lesions and normal-appearing white matter in multiple sclerosis	Werring DJ et al.	Neurology	1999	509	20.36
30	Meta-analysis of diffusion tensor imaging studies in schizophrenia	Ellison-Wright I. Bullmore ET	Schizophrenia Research	2009	507	33.8

Abbreviations: AC, average citations per year; PY, publication year; TC, total citation.

According to the keyword analyses, the most studied topics on DTI from past to present are FA, DTI tractography, white matter, brain, anisotropic diffusion, corpus callosum, spinal cord/spinal cord injury, ADC, tract-based spatial statistics (TBSS), corticospinal tract, Alzheimer's disease, mean diffusivity, multiple sclerosis, schizophrenia, fiber tracking, aging, stroke, traumatic

brain injury, functional magnetic resonance imaging (fMRI), and neuroimaging. Additional analysis with the biblioshiny library in the R studio software bibliometrix package involved dividing the past and present timeline into two distinct periods. Figure 5 visualizes the trend of keyword analysis obtained from 1980 through 2012 (Author's keywords, timespan 1980–2012, word

TABLE 4 The ranking of the 142 most frequently used keywords in diffusion tensor imaging (DTI) articles.

Keywords	N	Keywords	N	Keywords	N	Keywords	N
Diffusion tensor imaging (DTI)	3883	Myelin/myelination	52	Motor function	29	Diffusivity	20
Magnetic resonance imaging (MRI) or MR imaging	1114	Epilepsy	47	Segmentation	29	Executive function	20
Fractional anisotropy (FA)	697	Axial diffusivity	45	Cognitive impairment	28	Imaging	20
Tractography	569	Mild traumatic brain injury	43	Diffusion kurtosis imaging	28	Meta-analysis	20
White matter	486	Tensor	43	Kidney	28	Registration	20
Diffusion tensor magnetic resonance imaging (DTI MRI)	210	Thalamus	43	Optic nerve	28	Reliability	20
Brain	193	Magnetic resonance	42	Pediatric	28	Connectome	19
Anisotropic diffusion (anisotropy)	188	Reproducibility	42	Uncinate fasciculus	28	Graph theory	19
Diffusion	186	Autism spectrum disorder	41	Cerebral palsy	27	Neurodevelopment	19
Corpus callosum	185	Biomarker(s)	40	Cingulum	27	Myocardium	18
Diffusion tensor	175	Bipolar disorder	40	Glioblastoma	27	Nerve regeneration	18
Spinal cord/spinal cord injury	153	Brain tumor	40	Basal ganglia	26	Probabilistic tractography	18
Apparent diffusion coefficient (ADC)	148	Voxel-based morphometry	40	Human	26	Aphasia	17
Tract-based spatial statistics (TBSS)	139	Memory	38	Atlas	25	Cervical spinal cord	17
Corticospinal tract	132	Prognosis	38	Motor recovery	25	Mouse	17
Alzheimer's disease	128	Arcuate fasciculus	37	Cognitive function	24	Muscle	17
Mean diffusivity	127	Dementia	37	Deep brain stimulation	24	Facial nerve	16
Multiple sclerosis	117	Fornix	37	Temporal lobe epilepsy	24	Internal capsule	16
Schizophrenia	117	Depression	36	Transcranial magnetic stimulation	24	Maturation	16
Diffusion weighted imaging (DWI)	112	Diffuse axonal injury	36	Wallerian degeneration	24	Motion	16
Fiber tracking	111	Cerebellum	35	Demyelination	23	Neurodegeneration	16
Aging	100	Machine learning	35	Diffusion imaging	23	Noise	16
Stroke	99	Language	34	Major depressive disorder	23	Support vector machine	16
Traumatic brain injury	96	Neural regeneration	33	Superior longitudinal fasciculus	23	Trigeminal neuralgia	16
Functional magnetic resonance imaging (fMRI)	95	Brain development	32	Anatomy	22	Vestibular schwannoma	16
Neuroimaging	94	Cervical spondylotic myelopathy	32	Brain imaging	22	Asymmetry	15
Glioma	73	Gray matter	32	Carpal tunnel syndrome	22	Breast cancer	15
Amyotrophic lateral sclerosis	69	Magnetic resonance spectroscopy	32	Median nerve	22	Cardiac	15
Fiber tractography	69	Optic radiation	32	Brain injury	21	Eigenvalues	15

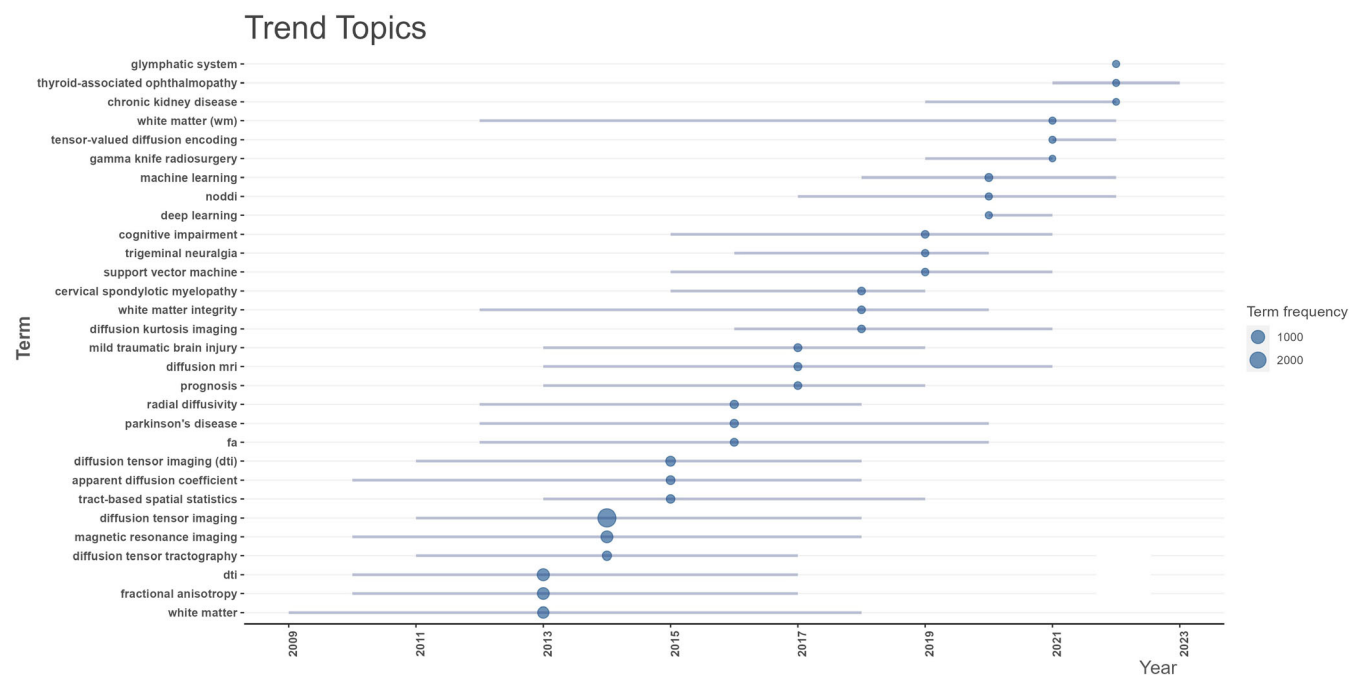


FIGURE 6 Trend keyword analysis for the period 2013–2022.

by the documents). The most cited keywords from the past to the present were aging, anisotropy, tensor, diffuse axonal injury, DTI tractography, internal capsule, neurodevelopment, myelin/myelination, autism, registration, human, brain MR, noise, and brain development. Figure 7D,E show the keyword burst analysis, where the latter demonstrates the hottest region in a larger size (VOSviewer: co-occurrence/author keywords: co-occurrences = 15, weights: total link strength). The keyword burst analysis revealed that MRI, FA, and white matter were the hottest topics in the field.

4 | DISCUSSION

The present study provides data about prominent research topics, past and current research trends, institutions, authors, and journals, publishing the highest number of DTI papers and receiving the highest number of citations. Such outputs have several significant aspects. First, the reported results help increase broader recognition of the vast possibilities of DTI among basic scientists and clinicians. Second, the reported findings guide the scientific community to find the papers that introduced the working principles of DTI or provided the most novel and influential results and to follow the leading scientists, institutions, and journals that intensively publish on this topic and report the most important results. A finding of the present study is that, despite the dominance of developing countries prolific in DTI publications, there is

significant global cooperation, including United States, European, and Asian countries. As the DTI publications from different countries correlated with GDP parameters, international collaboration is expected to increase in parallel to economic progress and accession to better equipment in developing countries, which shall be encouraged. The publication of relatively few DTI articles between 1980 and 1987 is attributable to the fact that the basic principles of diffusion MRI were introduced in the mid-1980s.¹ After 1987, DTI publications exerted an increasing trend until 2016, followed by a decrease until 2012. This decrease is not easily explicable but may be associated with the development of other sophisticated methods that compete with the interest in DTI. Yet, according to the analyses of the present study, a linear increase in DTI research trend is expected, which may occur with the incorporation of novel machine-learning methods into DTI applications, and the awareness of the vast potential of this modality among researchers and clinicians.

Fifteen of the first 18 countries that stood out in DTI global productivity were developed, and three (China, India, and Turkey) were developing countries. Still, all these countries have large economies. The high level of significant correlation between the number of articles on DTI and the GDP and GDP per capita of countries showed that the economic development of countries is effective in global productivity on DTI. The finding showing the highest numbers of DTI articles published by the University of California, Harvard University, and Johns

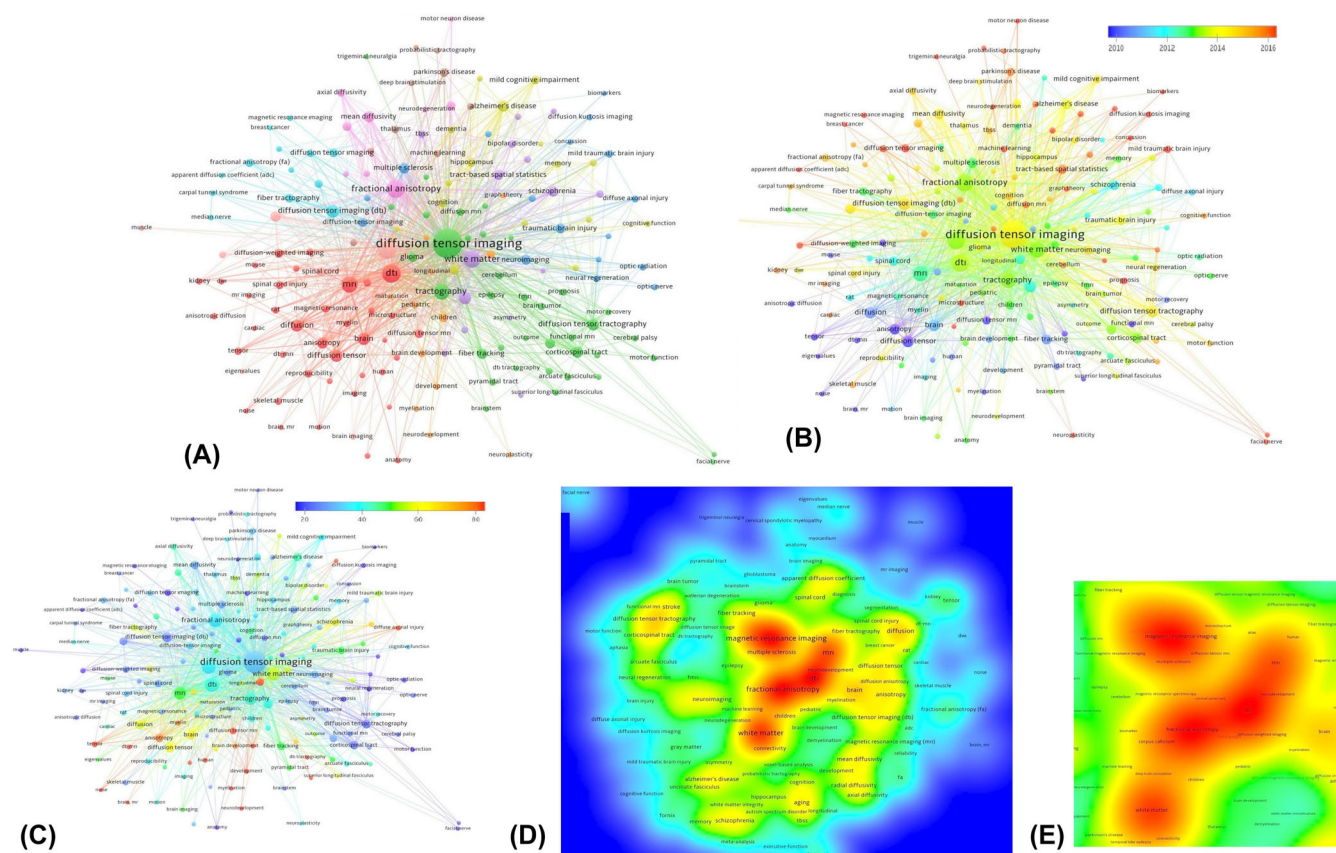


FIGURE 7 (A) Network visualization map showing clustering trends of diffusion tensor imaging (DTI) topics. Different clusters are shown in different colors. Similar colored keywords are in the same clusters. (B) A network visualization map showing past and current publication trends of DTI investigations. As the topicality of the investigations increases, the indicator in the lower right corner of the figure turns from blue to red (blue-green-yellow-red). (C) A network visualization map showing keywords found in the most cited articles on the DTI topic. As the number of citations the keyword receives increases, the indicator in the lower right corner of the figure turns from blue to red (blue-green-yellow-red). (D) Figure demonstrating the keyword burst analysis. (E) A larger depiction of the highest burst region. For subfigures (A), (B), and (C), the size of the circles positively correlates with the number of articles citing the analyzed keyword.

Hopkins University may be explicable by higher research grants and more advanced equipment in these institutions. This observation also parallels that the number of the reported DTI articles correlates with GDP and GDP per capita. The United States, European Countries (England, Germany, Netherlands, Switzerland, Italy, France, Sweden, Belgium, Spain), China, Canada, Australia, South Korea, and Japan are the leading countries of international cooperation. The cluster analysis for international collaborations revealed some collaborations between countries with close geographical borders, yet global partnerships were remarkable in the general clustering. This feature is easily understandable because the impact of geographical borders on international collaborations is almost lost in the Internet era.

The journals that stood out in terms of contribution to the literature on DTI regarding the number of published articles or the number of citations do not entirely overlap. The likely reason is that some journals like

“Biophysical Journal” or “Computer Methods and Programs in Biomedicine” focus more on the basic physical and computational principles of DTI and publish research that may break fresh ground for novel capabilities and applications of DTI. An alternative cause may be that journals such as “Brain Mapping” appeal to a smaller population of scientists and clinicians. Still, all the journals mentioned in the results section are highly qualified. Hence, these journals come to the fore for researchers who aim to reach a great scientific audience and obtain high citations. Similar to the situation observed for a partial mismatch regarding the number of publications and citations in different journals, the author names who published the most number or most cited articles only partially overlap. This mismatch is mostly not due to the quality of publications but rather because some publications are of interest to a smaller population of researchers. These articles may more likely relate to specific diseases or finite research areas such as

mapping particular brain areas. In contrast, highly cited articles mainly include groundbreaking research introducing the principles of DTI or reporting its novel applications, which received many more citations from researchers working in this area. Indeed, this fact becomes evident when looking at the titles of the most cited publications.

For instance, the most cited article on DTI belonging to Basser and colleagues is titled “MR diffusion tensor spectroscopy and Imaging” and published in the “Biophysical Journal,” which mainly publishes the fundamental discoveries in basic research.¹⁵ The second and third most cited DTI articles, both published in the “Journal of Magnetic Resonance Series B” also belong to Basser and Pierpaoli and Basser and colleagues, respectively.^{3,16} All these studies belong to the same team, and it is evident that these publications introduced the principles of DTI by looking at the titles “Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI” and “Estimation of the effective self-diffusion tensor from the NMR spin-echo.”^{3,16} The fourth and fifth most influential articles belonged to Pierpaoli et al. and Andersson et al., which are among the first studies about DTI employment in brain imaging and correcting distortions in spin-echo echo-planar images.^{17,18} Hence, it can be deduced that pioneering studies about the utilization and optimization of the DTI modality obtained more citations. When it comes to co-citations, it becomes apparent that the author names publishing the most influential studies are mostly the same obtained with citation analysis, which is an expected finding. According to the number of co-citations, the leading studies belonged to Basser and Pierpaoli (1996), Basser et al. (1994), Smith et al. (2006), Mori et al. (1999), Beaulieu (2002), Basser et al. (1994), Le Bihan et al. (2001), Pierpaoli et al. (1996), Pierpaoli and Basser (1996), and Smith et al. (2004).^{1,3,16,17,19–23} For researchers and clinicians aiming to study DTI, these articles are highly commendable to read.

According to the keyword analyses on research trends, it became apparent that earlier studies were related to fundamental aspects and the most clinically relevant applications of DTI, such as FA, anisotropic diffusion, ADC, TBSS, and DTI tractography. According to the present bibliometric study results, functional MRI studies and clinical studies, such as those conducted on Alzheimer's disease or schizophrenia, followed the establishment of the fundamental principles of DTI. For example, many studies employed DTI applications to discriminate normal brain shrinkage from Alzheimer's Disease, or to evaluate the extent and prognosis of post-traumatic diffuse axonal injury. After the establishment of DTI and its clinical utilization for differential

diagnosis and prognosis prediction first, studies increasingly began to emerge that aimed to achieve clues to understand the pathogenesis of diseases such as autism, cognitive impairment, major depression, and Parkinson's disease. Besides, DTI research also gained speed in understanding neurophysiology and neurodevelopment, such as determining myelination events in the central nervous system. The matching results of the keyword citation analysis with the keyword number trends highly indicate that DTI will have ever-enhancing applications for uncovering physiological conditions and pathologies associated with fewer morphological changes, but more remarkable changes at the macromolecular level. Hence, it would be plausible to anticipate that the DTI applications will play more significant roles in the future, both in basic and clinical sciences.

Indeed, the present bibliometric analyses on the keywords used in at least 15 different articles and the performed trend analyses encompassing the past 10 years provide essential insights that DTI applications may be ever more promising with the incorporation of continuously improving computational sciences. Notably, the trend analyses regarding the last 10 years revealed a considerable rise in DTI studies that involved artificial intelligence approaches, including support vector machine (SVM), deep learning, and machine learning. The reason for the perpetually enhancing studies combining artificial intelligence with DTI stems from the challenging complexity and high-dimensional nature of this technique. Artificial intelligence methods are inherently capable of generalizing learned patterns from training data. These automatic feature extraction capabilities allow deep-learning algorithms to yield highly relevant information from DTI data and help identify underlying patterns. Hence, several artificial intelligence applications are the sole promising approaches in defining and interpreting large, intricate datasets.

For instance, SVM analysis of the DTI data allows for a better classification of the brain regions and discerns healthy conditions from disease in several circumstances.^{24–26} One example is that the SVM-based DTI pattern recognition provided a highly accurate diagnosis of Parkinson's Disease among suspicious cases with clinical relevance.²⁴ Another exemplar is the application of ADC, FA, and radiomic feature-based machine-learning classifiers utilizing post-contrast T1-weighted (T1C) images to grade meningeal tumors.²⁵ Analyzing DTI with deep learning methods could also significantly help to inspect and discover complex brain connections and patterns. A novel proposed processing framework named DeepDTI strongly curtails the data requirement of six DWIs demanded for the canonical voxel-based fitting methods to derive the six unique unknowns of the DTI. Data-

driven supervised deep learning methods made such reduction of the data requirement possible.²⁶ Machine learning allows versatile DTI data identification and classification applications with promising implications, as evident from the results of the current bibliometric study. Hence, machine learning, TBSS, support vector machine, graph theory, and probabilistic tractography will further enhance DTI's ever-growing potential. For instance, increasing DTI's capabilities would significantly improve its implications in understanding the normal development and physiology and the pathologies of the nervous system. A more in-depth understanding of the healthy and abnormal myelination, white matter microstructure, neuroplasticity, neurodegenerative processes, and the regenerative capabilities of brain cells would be among the horizons for DTI application.

5 | LIMITATIONS AND STRENGTHS

One limitation of the present study is utilizing a single database (WoS) and not scanning others, such as PubMed and Scopus. On the WoS database, non-English articles are not obtainable by scanning articles in the original language, as the titles of these articles are translated into English. This feature may limit the analysis of global data. Not analyzing Scopus may have overlooked some relevant articles, because Scopus includes more records and journals than WoS. PubMed covers online articles before print, while WoS does not include online early versions. About 20% of the articles cited in PubMed may be unique and not present in Google Scholar, suggesting its broad coverage. These facts suggest possible limitations of omitting PubMed or Scopus analysis, as the in-depth detection capabilities of PubMed were not profited, and recent studies may have been missed. The reason for the employed literature search strategy was due to the inability to perform citation and co-citation analyses on documents downloaded from PubMed. Also, PubMed includes almost only biomedical studies, while WoS cites articles from all aspects of science. On that aspect, WoS research may provide more results on the physics of MRI and imaging modalities such as DTI. Additionally, WoS has more keywords relevant to the broad category of the manuscript subject than Scopus, which focuses more on the article content. Therefore, WoS analysis alone still allows a sufficient survey of the published articles. One may also consider that limiting the bibliometric analyses with WoS may have restricted the retrieval of the actual number of articles relevant to the study subject as the WoS citation period encompasses much later times than PubMed, which cites articles dating back to 1966 and

even way back to 1809 in very selective situations (as of May 2023). Nonetheless, this factor is not a limitation of the current research since the significant developments of DTI applications are relatively recent. Since WoS did not include publications before 1980, most WoS database studies start from 1980 or later. Therefore, the current investigation presented a bibliometric analysis of publications between 1980 and 2022. Before 1996, there were negligible articles (3 or fewer); thus, the analyzed research period in this study covers almost all articles on this subject. Considering Scopus, despite its more comprehensive coverage, it also cites publications with questionable impact and reliability. In that term, WoS is preferable to define studies published in journals with higher impact as it indexes nearly all SCI-expanded journals.²⁷ Lastly, the WoS database comprises about 90 million publications with over 12 000 high-impact journals. These facts suggest that, searching only the WoS database still provided an adequate amount of data regarding qualified research.

6 | CONCLUSIONS

This bibliometric study, analyzing 6586 articles on DTI, helps provide greater scope for both basic and clinical scientists regarding its constantly growing opportunities to perform in-depth research. The fast growth of DTI applications is likely attributable to its provision of essential data for comprehending the pathogenesis, predicting prognosis, and clinical follow-up of several diseases. Based on topics of highly cited DTI articles, it would be appropriate to propose that DTI has other solid potentials to provide information on neural tissue architecture and renewal, including but not limited to white matter integrity, microstructure, neuroplasticity, and neuroregeneration. Although not separated by sharp lines, it is suggestible that the past interest in DTI research has gone through three stages. At first, scientists focused on the fundamental establishment of this new technique. After that, studies aimed to benefit from this novel option for differential clinical diagnosis and prognosis prediction. Then, through the broader recognition of DTI potentials by the scientific community, a third phase of research activity started, which aimed to utilize this encouraging technique to understand mechanisms of normal human physiology and pathophysiology at the molecular level undetectable with conventional radiological modalities. Today, it would be possible to propose that a fourth stage of DTI research has begun in the era of artificial intelligence and machine learning. The great interest in utilizing artificial intelligence methodologies in DTI applications stems from their convenience in

analyzing big data. These methodologies can help improve neurological disease diagnosis and understanding of brain complexity. Despite being highly promising, these approaches may exert different reliabilities depending on the features of extraction methodology, model generalization capability, and the investigated dataset's size. Such issues need consideration for future basic and clinical studies. Yet, in all circumstances, it is undoubtful that artificial intelligence approaches will extend the applications and increase the relevance of DTI. The future occasions that DTI could provide will grow through shared research activities between different countries. Numerous shared DTI studies exist between countries, yet these collaborations are mainly limited to highly developed ones. Global scientific collaborations are much more accessible in the Internet era. Thus, developed countries should share their know-how on DTI with developing and underdeveloped countries to improve global health. Such collaborations will also benefit developed countries to know about rare diseases and collect global scientific information. In sum, this bibliometric research and succeeding studies may increase researchers' and clinicians' awareness of the broad capabilities of DTI and spark new ideas for future studies.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

PATIENT CONSENT STATEMENT

The submitted bibliometric work does not involve any human studies.

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How to cite this article: Özlük E, Özlük Gülşah Öztürk. Diffusion tensor imaging from past to present: A bibliometric analysis with trending topics and global productivity during 1980–2022. *Int J Imaging Syst Technol*. 2024;34(4):e23115. doi:[10.1002/ima.23115](https://doi.org/10.1002/ima.23115)