A scientometric analysis of the 100 most cited articles on magnetic resonance guided focused ultrasound

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Background: Diagnostic ultrasound has long been a part of a physician’s armamentarium, but transcranial focused ultrasound (FUS) is an emerging treatment of neurological disorders. Consequently, the literature in this field is increasing at a rapid pace.

Objective: This analysis was aimed to identify the top-cited articles on FUS to discern their origin, spread, current trends highlighting future impact of this novel neurosurgical intervention.

Methods: We searched the Web of Science database on 28th May 2021 and identified the top 100 cited articles. These articles were analyzed with various scientometric parameters like the authors, corresponding authors, country of corresponding author, journal of publication, year of publication. Citation based parameters including total citations, mean citations per article and mean citations, citation count, and the citation per year, citations per year and co-authors per document were studied as well in addition to Hirsch h-index, g-index, m-index, Bradford’s Law, Lotka’s law and Collaboration index.

Results: The 100 top-cited articles were published between 1998 and 2019 in 45 different journals. The average citations per document and citations per document per year were 97.78 and 12.47, respectively. The most prolific authors were Hynynen K (Medical Biophysics—Toronto), Elias WJ (Neurosurgery—Virginia), Zadicario (InSightec). The Journal of Neurosurgery published the most top-cited articles (n = 11), and most articles originated from the United States, followed by Canada. Among individual institutions, the University of Toronto was the most productive.

Conclusion: FUS is an emerging treatment of neurological disorders. With its increasing application, the FUS literature is increasing rapidly. Eleven countries contributed to the top 100 cited articles, with the top 2 countries (the United States and Canada) contributing to more than half of these articles.

Keywords: focused ultrasound, neurosurgery, Parkinson’s disease, essential tremor, MRI, FUS
Introduction

Diagnostic ultrasound has been a part of a physician’s armamentarium for the last seven decades. Focused ultrasound (FUS) has emerged as a therapeutic option in the last few decades to successfully ablate soft tissue tumors such as uterine fibroids, breast carcinoma, and bone metastases (Fry et al., 1958; Fry and Fry, 1960; Cline et al., 1992, 1993, 1995; Hynynen et al., 1993a,b). Technological advances including development of a phased spherical array with a multielement transducer helmet and the implementation of magnetic resonance imaging guidance for real-time tissue temperature monitoring led to intracranial application for neurological disorders, specifically the movement disorders (Clement and Hynynen, 2002; Lipsman et al., 2014). FUS has evolved rapidly in the recent years, specifically in the functional neurosurgery with significant clinical and research publication.

Bibliometrics is a methodological approach from the library sciences that statistically analyses the citation counts of books, articles, and other publications to determine the influence and impact of the scientific publications. Scientometrics is a subfield of bibliometrics that studies science publications by using bibliometric methods to find author, article, and journal-level metrics (i.e., H-index, citation index, and journal impact factor, respectively). It provides a broad overview of the field’s direction, complements the expert peer review process, and is transparent and objective. Many scientometric analyses have been published in neurosurgery to find the 100-most cited articles on topics like endoscopic third ventriculostomy, ossified posterior longitudinal ligament, pallidotomy, and cervical spondylotic myelopathy (Zagzoog et al., 2018; Chen et al., 2019; Agrawal et al., 2021; Garg et al., 2021, 2022a,b; Zhao et al., 2021). However, there is no such article published on transcranial FUS. This scientometric analysis presents the top 100 cited articles published on transcranial FUS and further reports the most significant contributors (authors, institutes, and countries) along with the various scientometric indices.

Materials and methods

Search strategy

A systematic search of the Web of Science database was performed on 28th May 2021. The keywords used for literature search were—“MR guided focused ultrasound,” “MRgFUS,” “Magnetic resonance-guided focused ultrasound,” “Ultrasound Thalamotomy,” “Ultrasound Thalamotomy for Essential Tremor,” “Ultrasound Subthalamotomy,” “focused ultrasound tremor,” “focused ultrasound tremor,” “ultrasound Parkinson,” “focused ultrasound ablation,” “transcranial focused ultrasound,” “focused ultrasound neuromodulation” and “focused ultrasound blood brain barrier opening.” The search results were screened and arranged in descending order of the number of citations, and articles were selected as per the following inclusion and exclusion criteria. FUS studies on transcranial FUS for neurological disorders, comparative study of FUS with DBS or radiofrequency (RF) for movement disorders, blood-brain barrier permeability, animal or cadaver research, targeted therapeutics and radiological aspect of FUS were included. FUS articles on non-cranial pathology were excluded.

Data and bibliometric parameters studied

The articles were arranged in descending order according to the number of citations. The various parameters analyzed were the title of the articles, authors, corresponding authors, country of corresponding author, journal of publication, year of publication. Citation based parameters including total citations, mean citations per article and mean citations, citation count, and the citation per year, citations per year and co-authors per document were studied as well. The following statistical parameters were considered during the analysis:

- Hirsch h-index: authors number of publications and number of citations, reviewed in other articles.
- g-index: is a variant of h-index which gives credit for the most cited papers. It is the highest rank where the sum of the citations is larger than the square of rank.
- m-index: is another variant of the h-index that displays h-index per year since first publication.
- Bradford’s Law: estimates the exponentially diminishing returns of searching for references in science journals was also studied.
- Lotka’s law: which denotes the distribution of the number of articles published by the number of authors.
- Collaboration index: it assigns a weighted credit to each author in a multi-author paper to capture a researcher’s scientific caliber better.

Analysis

The statistical analysis was performed using R software version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria) (Aria and Cuccurullo, 2017; R Core Team, 2022).

Results

Articles

The literature search yielded 2,500 articles, and we selected the 100 most cited articles which met the study inclusion and
| Paper                  | DOI                          | Article type | Journal          | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article                                                                 |
|-----------------------|------------------------------|--------------|------------------|------------------|----------------------|-----------------------------------|----------------|------------|---------------|---------------|----------------|-------------------------------------------------------------------------------------------------------------------------------------|
| HYNNYSEN K. 2001,     | 10.1148/radiol.220201804    | ARTICLE      | RADIOLOGY        | 2001             | HYNNYSEN, K          | HARV ARD UNIV, USA, USA            | 855            | 40.71      | 1             | Animal         | Blood-brain barrier | Noninvasive MR imaging-guided focal opening of the blood-brain barrier in rabbits                                                  |
| ELLIAS WJ, 2013,      | 10.1056/NEJMoa1300962        | ARTICLE      | NEW ENGL J MED   | 2013             | ELLIAS, WJ           | UNIV VIRGINIA, USA                | 385            | 42.78      | 2.984         | Human         | Movement disorder | A pilot study of focused ultrasound thalamotomy for essential tremor                                                              |
| ELLIAS WJ, 2016,      | 10.1056/NEJMoa1600159        | ARTICLE      | NEW ENGL J MED   | 2016             | ELLIAS, WJ           | UNIV VIRGINIA, USA                | 376            | 62.67      | 3.547         | Human         | Movement disorder | A randomized trial of focused ultrasound thalamotomy for essential tremor                                                        |
| MCDANNOLD N. 2010,    | 10.1227/01.NEU.0003603799.5800.2F | ARTICLE      | NEUROSURGERY     | 2010             | MCDANNOLD, N         | HARV ARD UNIV, USA                | 350            | 30         | 2.039         | Human         | Oncology        | Transcranial magnetic resonance imaging–guided focused ultrasound surgery of brain tumors: initial findings in 3 patients                         |
| LIPSMAN N, 2013,      | 10.1016/S1474-4422(13)70048-6 | ARTICLE      | LANCET NEUROL    | 2013             | LOZANO, AM           | UNIV TORONTO, CANADA              | 310            | 34.44      | 2.403         | Human         | Movement disorder | MR-guided focused ultrasound thalamotomy for essential tremor: a proof-of-concept study                                          |
| MARTIN E, 2009,       | 10.1002/ana.21801            | ARTICLE      | ANN NEUROL       | 2009             | MARTIN, E            | UNIV CHILDREN HOSP ZURICH,         | 286            | 22         | 2.424         | Human         | Pain            | High-intensity focused ultrasound for noninvasive functional neurosurgery                                                      |
| LIU HL. 2010, P       | 10.1073/pnas.1003388107      | ARTICLE      | P NATL ACAD SCI | 2010             | CHEN, PY             | CHANG GUNG UNIV, COLL MED         | 282            | 23.3       | 1.613         | Review - Animal | Blood-brain barrier | Magnetic resonance monitoring of focused ultrasound/magnetic nanoparticle targeting delivery of therapeutic agents to the brain |
| YOO SS, 2011,         | 10.1016/j.neuroimage.2011.02.058 | ARTICLE      | NEUROIMAGE       | 2011             | YOO, SS              | HARV ARD UNIV, USA                | 265            | 24.09      | 1.205         | Animal         | Stimulation     | Focused ultrasound modulates region-specific brain activity                                                                   |
| HYNNYSEN K, 2006,     | 10.3371/jna.2006.105.3.445   | ARTICLE      | J NEUROSURG      | 2006             | HYNNYSEN, K          | UNIV TORONTO, CANADA              | 231            | 14.44      | 1.351         | Animal         | Blood-brain barrier | Focal disruption of the blood-brain barrier due to 260-kHz ultrasound bursts: a method for molecular imaging and targeted drug delivery |
| MCDANNOLD N. 2005,    | 10.1016/j.ultrasoundmedbio.2005.07.010 | ARTICLE      | ULTRASOUND MED BIOL | 2005             | MCDANNOLD, N         | HARV ARD UNIV, USA                | 225            | 13.24      | 1             | Animal         | Blood-brain barrier | MRI-guided targeted blood-brain barrier disruption with focused ultrasound: Histological findings in rabbits                         |
| JORDAO JF. 2010,      | 10.1371/journal.pone.0010549 | ARTICLE      | PLOS ONE         | 2010             | JORDAO, JF           | SUNNYBROOK RES INST, TORONTO       | 221            | 18.42      | 1.264         | Animal         | Alzheimer's disease | Antibodies targeted to the brain with image-guided focused ultrasound reduces amyloid-beta plaque load in the TgCRND18 mouse model of Alzheimer's disease |
| Paper          | DOI                  | Article type | Journal / Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article                                                                 |
|---------------|----------------------|--------------|----------------------------|-----------------------|-------------------------------------|----------------|-------------|---------------|---------------|----------------|----------------------------------------------------------------------------------|
| LIPSMAN N, 2018, NAT COMMUN | 10.1038/s41467-018-04529-6 | ARTICLE      | NAT COMMUN 2018           | SUNNYBROOK RES INST    | UNIV TORONTO, CANADA                | 213            | 53.25       | 3.252         | Human         | Alzheimer's disease | Blood–brain barrier opening in Alzheimer's disease using MR-guided focused ultrasound |
| JEANMONOD D, 2012, NEUROSURG FOCUS | 10.3171/2011.10.FOCUS11248 | ARTICLE      | NEUROSURG FOCUS 2012      | JEANMONOD, D           | CTR ULTRASOUND FUNCT NEUROSURG, SWITZERLAND | 195            | 19.5        | 2.27          | Human         | Pain            | Transcranial magnetic resonance imaging–guided focused ultrasound: noninvasive central lateral thalamotomy for chronic neuropathic pain |
| BYSTRTSKY A, 2011, BRAIN STIMUL | 10.1016/j.bes.2011.03.007 | REVIEW       | BRAIN STIMUL 2011          | BYSTRITSKY, A          | UNIV CALIF LOS ANGELES, LOS ANGELES, USA | 175            | 15.91       | 0.795         | Human         | Neurostimulation review of low-intensity focused ultrasound pulsation |
| FAN CH, 2013, BIOMATERIALS | 10.1016/j.biomaterials.2013.01.099 | ARTICLE      | BIOMATERIALS 2013          | YEH, CK                | NATL TSING HUA UNIV, TAIWAN         | 158            | 17.56       | 1.225         | Animal        | Blood-brain barrier | SPION-conjugated, doxorubicin-loaded microbubbles for concurrent MRI and focused-ultrasound enhanced brain-tumor drug delivery |
| TREAT LH, 2012, ULTRASOUND MED BIOL | 10.1016/j.ultrasoundmedbio.2012.04.015 | ARTICLE      | ULTRASOUND MED BIOL 2012  | MCDANNOLOD, N          | HARV UNIV, USA, USA                 | 158            | 15.8        | 1.84          | Animal        | Blood-brain barrier | Improved anti-tumor effect of liposomal doxorubicin after targeted blood-brain barrier disruption by MRI-guided focused ultrasound in rat glioma |
| HYNYNEN K, 2006, EUR J RADIOL | 10.1016/j.euradiol.2006.04.007 | ARTICLE      | EUR J RADIOL 2006          | HYNYNEN, K             | HARV UNIV, USA, USA                 | 157            | 9.81        | 0.918         | Animal        | Technique        | Pre-clinical testing of a phased array ultrasound system for MRI-guided noninvasive surgery of the brain— a primate study |
| KOVACS ZI, 2017, P NATL ACAD SCI USA | 10.1073/pnas.1614777114 | ARTICLE      | P NATL ACAD SCI USA 2017  | KOVACS, ZI             | NIH, FRANK LAB, RADIOL & IMAGING SCI, US | 143            | 28.6        | 2.566         | Animal        | Blood-brain barrier | Disrupting the blood–brain barrier by focused ultrasound induces sterile inflammation |
| NANCE E, 2014, J CONTROL RELEASE | 10.1016/j.jconrel.2014.06.031 | ARTICLE      | J CONTROL RELEASE 2014     | PRICE, RJ              | UNIV VIRGINIA, USA                  | 131            | 16.38       | 2.012         | Animal        | Blood-brain barrier | Non-invasive delivery of stealth, brain-penetrating nanoparticles across the blood-brain barrier using MRI-guided focused ultrasound |
| BURGESS A, 2014, RADIOLOGY | 10.1148/radiol.14140245 | ARTICLE      | RADIOLOGY 2014             | BURGESS, A             | SUNNYBROOK RES INST, TORONTO         | 130            | 16.25       | 1.997         | Animal        | Alzheimer's disease | Alzheimer's disease in a mouse model: MR imaging–guided focused ultrasound targeted to the hippocampus opens the blood–brain barrier and improves pathologic abnormalities and behavior |
| Paper | DOI | Article type | Journal | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article |
|-------|-----|--------------|---------|------------------|----------------------|-------------------------------------|-----------------|-------------|---------------|--------------|---------------|----------------|
| MAINPRIZE T, 2019, SCI REP-UK | 10.1038/s41598-018-36340-0 | ARTICLE | SCI REP-UK | 2019 | MAINPRIZE, T SUNNYBROOK HLT SCI CTR, CANADA | 129 | 43 | 2.449 | Human | Oncology | Blood-brain barrier opening in primary brain tumors with non-invasive MR-guided focused ultrasound: a clinical safety and feasibility study |
| RAM Z, 2006, NEUROSURGERY | 10.1227/01.NEU.0000254439.02736.D8 | ARTICLE | NEUROSURGERY | 2006 | RAM, Z TEL AVIV SOURASKY MED CTR, ISRAEL | 125 | 7.81 | 0.731 | Human | Oncology | Magnetic resonance imaging-guided, high-intensity focused ultrasound for brain tumor therapy |
| PARK EJ, 2012, J CONTROL RELEASE | 10.1016/j.jconrel.2012.09.007 | ARTICLE | J CONTROL RELEASE | 2012 | PARK, EJ HARV ARD UNIV, USA, USA | 113 | 11.3 | 1.316 | Animal | Blood-brain barrier | Ultrasound-mediated blood-brain/blood-tumor barrier disruption improves outcomes with trastuzumab in a breast cancer brain metastasis model |
| LEINENGA G, 2016, NAT REV NEUROL | 10.1038/nrneurol.2016.13 | REVIEW | NAT REV NEUROL | 2016 | GOTZ, J UNIV QUEENSLAND, AUSTRALIA | 109 | 18.17 | 1.028 | Review | | Ultrasound treatment of neurological diseases — current and emerging applications |
| CHANG WS, 2015, J NEUROL NEUROSUR PS | 10.1136/jnnp-2014-307642 | ARTICLE | J NEUROL NEUROSUR PS | 2015 | CHANG, PW YONSEI UNIV, SOUTH KOREA | 109 | 15.57 | 1.697 | Human | Movement disorder | Unilateral magnetic resonance guided focused ultrasound thalamotomy for essential tremor: practices and clinicoradiological outcomes |
| OBESO JA, 2017, MOVEMENT DISORD | 10.1002/mds.27115 | REVIEW | MOVEMENT DISORD | 2017 | OBESO, JA HOSP UNIV HM PUERTA SUR, SPAIN | 102 | 20.4 | 1.83 | Review | Movement disorder | Past, present, and future of Parkinson’s disease: a special essay on the 200th anniversary of the shaking palsy |
| MCDANNOLD N, 2007, ULTRASOUND MED BIOL | 10.1016/j.ultrasmedbio.2006.10.004 | ARTICLE | ULTRASOUND MED BIOL | 2007 | MCDANNOLD, N BRIGHAM & WOMENS HOSP USA | 96 | 6.4 | 1.401 | Animal | Blood-brain barrier | Use of ultrasound pulses combined with definity for targeted blood-brain barrier disruption: a feasibility study |
| JUNG HH, 2015, MOL PSYCHIATR | 10.1038/mp.2014.154 | ARTICLE | MOL PSYCHIATR | 2015 | KIM, CH INST BEHAV SCI MED, SOUTH KOREA | 88 | 12.57 | 1.57 | Human | OCD | Bilateral thermal capsulotomy with MR-guided focused ultrasound for patients with treatment-refractory obsessive-compulsive disorder: a proof-of-concept study |
| BOND AE, 2017, JAMA NEUROL | 10.1001/jamaneurol.2017.3098 | ARTICLE | JAMA NEUROL | 2017 | ELIAS, WJ UNIV VIRGINIA, USA | 87 | 17.4 | 1.561 | Human | Movement disorder | Safety and efficacy of focused ultrasound thalamotomy for patients with medication-refractory, tremor-dominant Parkinson’s disease |

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| Paper          | DOI                      | Article type | Journal            | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study       | Theme of study               | Title of article                                                                 |
|----------------|--------------------------|--------------|--------------------|------------------|----------------------|-------------------------------------|-----------------|-------------|---------------|---------------------|----------------------------------|--------------------------------------------------------------------------------|
| SUN T, 2017, P NATL ACAD SCI USA | 10.1073/pnas.1713328114 | ARTICLE      | P NATL ACAD SCI USA | 2017             | SUN, T               | HARV UNIV, USA, USA                 | 87              | 17.4        | 1.561         | Animal              | Blood-brain barrier              | Closed-loop control of targeted ultrasound drug delivery across the blood-brain/tumor barriers in a rat glioma model |
| MEAD BP, 2016, J CONTROL RELEASE | 10.1016/j.jconrel.2015.12.034 | ARTICLE      | J CONTROL RELEASE  | 2016             | PRICE, RJ            | UNIV VIRGINIA, USA                  | 81              | 13.5        | 0.764         | Animal              | Blood-brain barrier              | Targeted gene transfer to the brain via the delivery of brain-penetrating DNA nanoparticles with focused ultrasound |
| ZAAROOR M, 2018, J NEUROSURG | 10.3171/2016.10JNS16758 | ARTICLE      | J NEUROSURG        | 2018             | ZAAROOR, M           | RAMBAM HLTH CARE CAMPUS, ISRAEL      | 80              | 20          | 1.221         | Human               | Movement disorder               | Magnetic resonance-guided focused ultrasound thalamotomy for tremor: a report of 30 Parkinson's disease and essential tremor cases |
| MARSAC L, 2012, MED PHYS | 10.1118/1.3674988     | ARTICLE      | MED PHYS           | 2012             | MARSAC, L            | UNIV PARIS, FRANCE                  | 79              | 7.9         | 0.92          | Human               | Technique                      | MR-guided adaptive focusing of therapeutic ultrasound beams in the human head |
| MEI I, 2009, J ULTRAS MED | 10.7863/jum.2009.28.7.871 | ARTICLE      | J ULTRAS MED       | 2009             | CHENG, Y             | CHONGQING MED UNIV, PEOPLES R CHINA | 76              | 5.85        | 0.644         | Animal              | Blood-brain barrier              | Experimental study on targeted methotrexate delivery to the rabbit brain via magnetic resonance imaging–guided focused ultrasound |
| JAGANNATHAN J, 2009, NEUROSURGERY | 10.1227/01.NEU.000336766.18197.8E | REVIEW      | NEUROSURGERY       | 2009             | KASSELL, NF          | UNIV VIRGINIA, USA                   | 76              | 5.85        | 0.644         | Review              | High-intensity focused ultrasound surgery of the brain: part 1—a historical perspective with modern applications |
| CHANG WS, 2016, J NEUROSURG | 10.3171/2015.3JNSI42592 | ARTICLE      | J NEUROSURG        | 2016             | CHANG, JW            | YUNSEI UNIV, SOUTH KOREA            | 75              | 12.5        | 0.708         | Human               | Technique                      | Factors associated with successful magnetic resonance-guided focused ultrasound treatment: efficiency of acoustic energy delivery through the skull |
| ARVANITIS CD, 2013, PHYS MED BIOL | 10.1088/0031-9155/50/14/4749 | ARTICLE      | PHYS MED BIOL      | 2013             | ARVANITIS, CD        | HARV UNIV, USA, USA                  | 75              | 8.33        | 0.581         | Human               | Blood-brain barrier              | Combined ultrasound and MR imaging to guide focused ultrasound therapies in the brain |
| MARTINEZ-FERNANDEZ R, 2018, LANCET NEUROL | 10.1016/S1474-4422(17)30403-9 | ARTICLE      | LANCET NEUROL      | 2018             | OREBO, JA            | UNIV HOSP HM PUERTA DEL SUR, SPAIN   | 72              | 18          | 1.099         | Human               | Movement disorder               | Focused ultrasound subthalamotomy in patients with asymmetric Parkinson's disease: a pilot study |

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TABLE 1 (Continued)

| Paper | DOI | Journal type | Journal | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article |
|-------|-----|--------------|---------|------------------|----------------------|--------------------------------------|----------------|------------|--------------|--------------|----------------|------------------|
| GHANOUNI P, 2015, AM J ROENTGENOL | 10.2214/AJR.14.13632 | REVIEW | AM J ROENTGENOL | 2015 | WINTERMARK, M | STANFORD UNIV, USA | 71 | 10.14 | 1.106 | Review | Transcranial MRI-guided focused ultrasound: a review of the technologic and neurologic applications |
| SCARCELLI T, 2014, BRAIN STIMUL | 10.1016/j.brs.2013.12.012 | ARTICLE | BRAIN STIMUL | 2014 | HYNYNEN, K | UNIV TORONTO, CANADA | 70 | 8.75 | 1.075 | Animal | Stimulation of hippocampal neurogenesis by transcranial focused ultrasound and microbubbles in adult mice |
| KONOFOGOU EE, 2012, CURR PHARM BIOTECHNO | | REVIEW | CURR PHARM BIOTECHNO | 2012 | KONOFOGOU, EE | COLUMBIA UNIV, USA | 70 | 7 | 0.815 | Review | Blood-brain barrier | Ultrasound-induced blood-brain barrier opening |
| ABRHAO A, 2019, NAT COMMUN | 10.1038/s41467-019-12426-9 | ARTICLE | NAT COMMUN | 2019 | ABRHAO, A | UNIV TORONTO, CANADA | 69 | 23 | 1.31 | Human | Blood-brain barrier | First-in-human trial of blood-brain barrier opening in amyotrophic lateral sclerosis using MR-guided focused ultrasound |
| MONTEITH S, 2013, J NEUROSURG | 10.3171/2012.10.JNS12449 | REVIEW | J NEUROSURG | 2013 | MONTEITH, S | UNIV VIRGINIA, USA | 67 | 7.44 | 0.519 | Review | Potential intracranial applications of magnetic resonance-guided focused ultrasound surgery |
| HERTZBERG Y, 2010, MED PHYS | 10.1118/1.3395553 | ARTICLE | MED PHYS | 2010 | NAVON, G | TEL AVIV UNIV, ISRAEL | 67 | 5.58 | 0.383 | Animal | Technique | Ultrasound focusing using magnetic resonance acoustic radiation force imaging: application to ultrasound transcranial therapy |
| LARRAT B, 2010, PHYS MED BIOL | 10.1088/0031-9007/55/2/003 | ARTICLE | PHYS MED BIOL | 2010 | LARRAT, B | UNIV PARIS, FRANCE | 65 | 5.42 | 0.372 | Animal | Technique | MR-guided transcranial brain HIFU in small animal models |
| FAN CH, 2016, THERANOSTICS | 10.7150/thno.15297 | ARTICLE | THERANOSTICS | 2016 | YEH, CK | NATL TSING HUA UNIV, TAIWAN | 64 | 10.67 | 0.604 | Animal | Blood-brain barrier | Ultrasound/magnetic targeting with SPIO-Dox-microbubble complex for image-guided drug delivery in brain tumors |
| KRISHNA V, 2018, JAMA NEUROL | 10.1001/jamaneurol.2017.3129 | REVIEW | JAMA NEUROL | 2018 | KRISHNA, V | OHIO STATE UNIV, USA | 63 | 15.75 | 0.962 | Review | A review of the current therapies, challenges, and future directions of transcranial focused ultrasound technology |

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| Paper | DOI | Article type | Journal | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article |
|-------|-----|--------------|---------|------------------|----------------------|----------------------------------|----------------|------------|--------------|---------------|----------------|-----------------|
| WINTERMARK M, 2014, AM J NEURORADIOL | 10.3174/ajnr.A3808 | ARTICLE | AM J NEURORADIOL | 2014 | WINTERMARK, M | UNIV VIRGINIA, USA | 63 | 7.88 | 0.968 | Human | Movement disorder | Imaging findings in MR imaging-guided focused ultrasound treatment for patients with essential tremor |
| FAN CH, 2016, SCI REP-UK | 10.1038/sep19579 | ARTICLE | SCI REP-UK | 2016 | LIU HL | CHANG GUNG UNIV, TAIWAN | 62 | 10.33 | 0.585 | Animal | Blood-brain barrier | Noninvasive, targeted and non-viral ultrasound-mediated GDNF-plasmid delivery for treatment of Parkinson’s disease |
| HUSS DS, 2015, MOVEMENT DISORD | 10.1002/mds.26455 | ARTICLE | MOVEMENT DISORD | 2015 | ELIAS, WJ | UNIV VIRGINIA, USA | 60 | 8.57 | 0.934 | Human | Movement disorder | Functional assessment and quality of life in essential tremor with bilateral or unilateral DBS and focused ultrasound thalamotomy |
| HUANG Q, 2012, EXP NEUROL | 10.1016/j.expneurol.2011.10.027 | ARTICLE | EXP NEUROL | 2012 | CHENG, Y | CHONGQING MED UNIV, PEOPLES R CHINA | 58 | 5.8 | 0.675 | Animal | Blood-brain barrier | Targeted gene delivery to the mouse brain by MRI-guided focused ultrasound-induced blood-brain barrier disruption |
| SAMIOTAKI G, 2015, J CEREBR BLOOD F MET | 10.1038/jcbfm.2014.236 | ARTICLE | J CEREBR BLOOD F MET | 2015 | KONOFOGOU, EE | COLUMBIA UNIV, USA | 57 | 8.14 | 0.888 | Animal | Blood-brain barrier | Enhanced delivery and bioactivity of the neurturin neurotrophic factor through focused ultrasound—brain barrier opening in vivo |
| CHANG JW, 2018, ANN NEUROL | 10.1002/ana.25126 | ARTICLE | ANN NEUROL | 2018 | CHANG, JW | YONSEI UNIV, SOUTH KOREA | 55 | 13.75 | 0.84 | Human | Movement disorder | A prospective trial of magnetic resonance-guided focused ultrasound thalamotomy for essential tremor: results at the 2-year follow-up |
| JONES RM, 2018, THERANOSTICS | 10.7150/thno.24911 | ARTICLE | THERANOSTICS | 2018 | JONES, RM | SUNNYBROOK RES INST, CANADA | 55 | 13.75 | 0.84 | Animal | Blood-brain barrier | Three-dimensional transcranial microbubble imaging for guiding volumetric ultrasound-mediated blood-brain barrier opening |
| KYRIAKOU A, 2014, INT J HYPERTHER | 10.3109/0266736.2013.861519 | REVIEW | INT J HYPERTHER | 2014 | KYRIAKOU, A | ITIS FDN RES INFORMAT TECHNOL SOC, SWITZERLAND | 55 | 6.88 | 0.845 | Review | | A review of numerical and experimental compensation techniques for skull-induced phase aberrations in transcranial focused ultrasound |

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| Paper                  | DOI                          | Article type | Journal                  | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study                                                                 |
|-----------------------|------------------------------|--------------|--------------------------|------------------|----------------------|-------------------------------------|-----------------|-------------|---------------|---------------|-----------------------------------------------------------------------------|
| XIE F, 2008, ULTRASOUND MED BIOL | 10.1016/j.ultrasmedbio.2008.05.004 | ARTICLES     | ULTRASOUND MED BIOL      | 2008             | PORTER, TR          | UNIV NEBRASKA, USA                 | 55              | 3.93        | 1             | Animal        | Blood-brain barrier Effects of transcranial ultrasound and intravenous microbubbles on blood-brain barrier permeability in a large animal model |
| SCHLESINGER I, 2015, PARKINSONS DIS-US | 10.1155/2015/219149         | ARTICLES     | PARKINSONS DIS-US        | 2015             | SCHLESINGER, I      | RAMBAM HEALTH CARE CAMPUS, ISRAEL   | 54              | 7.71        | 0.841         | Human         | Movement disorder MRI guided focused ultrasound thalamotomy for moderate-to-severe tremor in Parkinson’s disease |
| DIAZ RJ, 2014, NANO MED NANO TECHNOLOGY | 10.1016/j.nano 2013.12.006 | ARTICLES     | NANO MED NANO TECHNOLOGY | 2014             | RUTKA, JF           | UNIV TORONTO, CANADA, CANADA       | 54              | 6.75        | 0.829         | In vivo       | Blood-brain barrier Focused ultrasound delivery of Raman nanoparticles across the blood-brain barrier: potential for targeting experimental brain tumors |
| DEFFIEUX T, 2010, IEEE T ULTRASON FER | 10.1109/TUFFC.2010.1738     | ARTICLES     | IEEE T ULTRASON FER      | 2010             | DEFFIEUX, T         | COLUMBIA UNIV, USA                 | 54              | 4.5         | 0.309         | Animal and Human skulls | Blood-brain barrier Numerical study of a simple transcranial focused ultrasound system applied to blood-brain barrier opening |
| LEGON W, 2018, HUM BRAIN MAPP | 10.1002/hbm.23981           | ARTICLES     | HUM BRAIN MAPP           | 2018             | LEGON, W            | UNIV VIRGINIA, USA                 | 53              | 13.25       | 0.809         | Human         | Neuromodulation with single-element transcranial focused ultrasound in human thalamus |
| MEAD RP, 2017, NANO LETTERS | 10.1021/acs.nanolett.7b00616 | ARTICLES     | NANO LETTERS             | 2017             | HANES, J; PRICE, RJ | JOHNS HOPKINS UNIV, USA, UNIV VIRGINIA, USA | 52              | 10.4        | 0.933         | Animal        | Blood-brain barrier Novel focused ultrasound gene therapy approach noninvasively restores dopaminergic neuron function in a rat Parkinson’s disease model |
| LIN CY, 2016, J CONTROL RELEASE | 10.1016/j.jconrel.2016.05.052 | ARTICLES     | J CONTROL RELEASE        | 2016             | LIU, HL             | CHANG GUNG UNIV, TAIWAN            | 51              | 8.5         | 0.481         | Animal        | Blood-brain barrier Non-invasive, neuron-specific gene therapy by focused ultrasound-induced blood-brain barrier opening in Parkinson’s disease mouse model |
| ELIAS WJ, 2013, J NEUROSURG | 10.3171/2013.5.JNS122327     | ARTICLES     | J NEUROSURG              | 2013             | ELIAS, WJ           | UNIV VIRGINIA, USA                 | 51              | 5.67        | 0.395         | Animal        | Lesion size A magnetic resonance imaging, histological, and dose modeling comparison of focused ultrasound, radiofrequency, and Gamma Knife radiosurgery lesions in swine thalami A magnetic resonance imaging, histological, and dose modeling comparison of focused ultrasound, radiofrequency, and Gamma Knife radiosurgery lesions in swine thalami |
| SUN T, 2015, PHYS MED BIOL | 10.1088/0031-9155/60/23/9079 | ARTICLES     | PHYS MED BIOL            | 2015             | SUN, T              | HAVARD UNIV, USA, USA              | 50              | 7.14        | 0.779         | Animal        | Blood-brain barrier Acoustic cavitation-based monitoring of the reversibility and permeability of ultrasound-induced blood-brain barrier opening |

(Continued)
| Paper                        | DOI                          | Article type | Journal               | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study     | Theme of study                     | Title of article                                                                 |
|-----------------------------|------------------------------|--------------|-----------------------|------------------|----------------------|------------------------------------|-----------------|-------------|---------------|-----------------|-----------------------------------|--------------------------------------------------------------------------------|
| MCDANNOLD N, 2003, MAGNET RESON MED | 10.1002/mrm.10453 | ARTICLE      | MAGNET RESON MED      | 2003             | MCDANNOLD, N         | BRIGHAM & WOMENS HOSP, USA         | 48              | 2.53        |               | Animal Technique | MRI-guided focused ultrasound surgery in the brain: tests in a primate model |
| BOUTET A, RANJAN M, 2018, BRAIN | 10.1093/brain/awy278       | ARTICLE      | BRAIN                 | 2018             | LOZANO, AM           | UNIV TORONTO, CANADA, CANADA        | 47              | 11.75       | 0.718         | Human Movement disorder | Focused ultrasound thalamotomy location determines clinical benefits in patients with essential tremor |
| TIMBIE KF, 2017, J CONTROL RELEASE | 10.1016/j.jconrel.2017.03.017 | ARTICLE, PROCEEDINGS RELEASE PAPER | J CONTROL RELEASE | 2017             | PRICE, RJ            | UNIV VIRGINIA, USA                 | 46              | 9.2         | 0.825         | Animal Blood-brain barrier | MR image-guided delivery of cisplatin-loaded brain-penetrating nanoparticles to invasive glioma with focused ultrasound |
| JUNG HH, 2015, J NEUROSURG | 10.3171/2014.8.JNS132603 | ARTICLE      | J NEUROSURG           | 2015             | CHANG, JW            | YONSEI UNIV, SOUTH KOREA            | 45              | 6.43        | 0.701         | Human Movement disorder | Different magnetic resonance imaging patterns after transcranial magnetic resonance-guided focused ultrasound of the ventral intermediate nucleus of the thalamus and anterior limb of the internal capsule in patients with essential tremor or obsessive-compulsive disorder |
| NA YC, 2015, NEUROLOGY | 10.1212/WNL.0000000000001826 | EDITORIAL MATERIAL | NEUROLOGY          | 2015             | CHANG, JW            | YONSEI UNIV, SOUTH KOREA            | 44              | 6.29        | 0.685         | Human Movement disorder | Unilateral magnetic resonance-guided focused ultrasound pallidotomy for Parkinson's disease |
| CHAUVET D, 2013, J NEUROSURG | 10.3171/2013.1.JNS12559 | ARTICLE      | J NEUROSURG           | 2013             | AUBRY, JF            | ESPCI, INST LANGEVIN, FRANCE        | 43              | 4.78        | 0.333         | Human Technique | Targeting accuracy of transcranial magnetic resonance-guided high-intensity focused ultrasound brain therapy: a fresh cadaver model |
| HUANG YX, 2017, RADIOLoGY | 10.1148/radul.2016152154 | ARTICLE      | RADIOLoGY            | 2017             | HUANG, YX            | SUNNYBROOK RES INST, CANADA         | 42              | 8.4         | 0.754         | Human Blood-brain barrier | Opening the blood-brain barrier with MR imaging-guided focused ultrasound: preclinical testing on a trans-human skull porcine model |
| CHAZEN JL, 2018, J NEUROSURG | 10.3171/2017.4.JNS162803 | ARTICLE      | J NEUROSURG           | 2018             | CHAZEN, JL           | Weill Cornell Medicine, USA         | 41              | 10.25       | 0.626         | Human Movement disorder | Clinical improvement associated with targeted interruption of the cerebellothalamic tract following MR-guided focused ultrasound for essential tremor |

(Continued)
| Paper | DOI | Article type | Journal | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article |
|-------|-----|--------------|---------|------------------|----------------------|-------------------------------------|----------------|------------|--------------|--------------|--------------|-----------------|
| COHEN ZR, 2007, NEUROSURGERY | 10.1227/01 NEU/0000245608.99946.C6 | ARTICLE | NEUROSURGERY | 2007 | RAM, Z | TEL AVIV MED CTR & SCH MED, ISRAEL | 41 | 2.73 | 0.599 | Animal | Technique | Magnetic resonance imaging-guided focused ultrasound for thermal ablation in the brain: a feasibility study in a swine model |
| COLUCCIA D, 2018, NANO-MED, NANOTECHNOLOGY | 10.1016/j.nano.2018.01.021 | ARTICLE | NANO-MED, NANOTECHNOLOGY | 2018 | RUTKA, JT | HOSP SICK CHILDREN, CANADA | 40 | 10 | 0.611 | Animal | Blood-brain barrier | Enhancing glioblastoma treatment using cisplatin-gold-nanoparticle conjugates and targeted delivery with magnetic resonance-guided focused ultrasound |
| MONTTEITH SJ, 2013, J NEUROSURG | 10.3171/2012.12 JNSI121095 | ARTICLE | J NEUROSURG | 2013 | MONTTEITH, S | UNIV VIRGINIA, USA | 40 | 4.44 | 0.31 | Animal | ICH | Minimally invasive treatment of intracerebral hemorrhage with magnetic resonance-guided focused ultrasound |
| LIPSMAN N, 2014, NEUROTHERAPEUTICS | 10.1007/s13311-014-0281-2 | REVIEW | NEUROTHERAPEUTICS | 2014 | LIPSMAN, N | UNIV TORONTO, CANADA, CANADA | 39 | 4.88 | 0.599 | Review | | Intracranial applications of magnetic resonance-guided focused ultrasound |
| PULKKINEN A, 2014, PHYS MED BIOL | 10.1088/0031-9155/59/7/1615 | ARTICLE | PHYS MED BIOL | 2014 | PULKKINEN, A | UNIV EASTERN FINLAND, FINLAND | 39 | 4.88 | 0.599 | Human | Technique | Numerical simulations of clinical focused ultrasound functional neurosurgery |
| RAYKUMAR VK, 2017, MOVEMENT DISORD | 10.1002/mds.26997 | ARTICLE | MOVEMENT DISORD | 2017 | HALPERN, CH | STANFORD UNIV, USA | 38 | 7.6 | 0.682 | Human | Movement disorder | Cost-effectiveness of focused ultrasound, radiosurgery, and DBS for essential tremor |
| WINTERMARK M, 2014, RADIOLOGY | 10.1148/radiol.14132112 | ARTICLE | RADIOLOGY | 2014 | WINTERMARK, M | UNIV VIRGINIA, USA | 37 | 4.62 | 0.568 | Human | Movement disorder | Thalamic connectivity in patients with essential tremor treated with MR imaging-guided focused ultrasound: in vivo fiber tracking by using diffusion-tensor MR imaging |
| MEDEL R, 2012, NEUROSURGERY | 10.1227/NEU/0000382672ac9 | REVIEW | NEUROSURGERY | 2012 | KASSELL, NF | UNIV VIRGINIA, USA | 37 | 3.7 | 0.431 | Review | | Magnetic resonance-guided focused ultrasound surgery: Part 2: a review of current and future applications |
| FAN CH, 2017, J CONTROL RELEASE | 10.1016/j.jconrel.2017.07.004 | REVIEW | J CONTROL RELEASE | 2017 | YEH, CK | NATL TSING HUA UNIV, TAIWAN | 36 | 7.2 | 0.646 | Review | | Ultrasound targeted CNS gene delivery for Parkinson's disease treatment |
| DEVARAKONDA SB, 2017, NANO LETT | 10.1021/acs.nanolett.7b00272 | ARTICLE | NANO LETT | 2017 | BANERJEE, RK | UNIV CINCINNATI, USA | 36 | 7.2 | 0.646 | Phantom | Technique | Assessment of gold nanoparticle-mediated-enhanced hyperthermia using MR-guided high-intensity focused ultrasound ablation procedure |

(Continued)
| Paper | DOI | Article type | Journal | Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article |
|-------|-----|--------------|---------|------------------|----------------------|--------------------------------------|----------------|------------|--------------|--------------|---------------|-----------------|
| ALLI S, 2018, J CONTROL RELEASE | 10.1016/j.jconrel.2018.05.005 | ARTICLE | J CONTROL RELEASE | 2018 | RUTKA, JT | HOSP SICK CHILDREN/CANADA | 35 | 8.75 | 0.534 | Animal | Blood-brain barrier disruption using focused ultrasound: a demonstration of feasibility and enhanced doxorubicin delivery | Brainstem blood brain barrier disruption using focused ultrasound: a demonstration of feasibility and enhanced doxorubicin delivery |
| O'REILLY MA, 2017, J ULTRAS MED | 10.7863/ultra.16.02005 | ARTICLE | J ULTRAS MED | 2017 | O'REILLY, MA | SUNNYBROOK RES INST, CANADA | 35 | 7 | 0.628 | Animal | Blood-brain barrier closure time after controlled ultrasound-induced opening is independent of opening volume | Blood-brain barrier closure time after controlled ultrasound-induced opening is independent of opening volume |
| MOROCZ IA, 1998, J MAGN RESON IMAGING | 10.1002/jmri.188080126 | ARTICLE | J MAGN RESON IMAGING | 1998 | JOLESZ, FA | HARVARD UNIV, USA, USA | 35 | 1.46 | 1 | Animal | Complications | Brain edema development after MRT-guided focused ultrasound treatment |
| WANG F, 2009, J ULTRAS MED | 10.7863/jum.2009.28.11.1501 | ARTICLE | J ULTRAS MED | 2009 | CHENG, Y | CHONGQING MED UNIV,PEOPLES R CHINA | 34 | 2.62 | 0.288 | Animal | Blood-brain barrier | Focused ultrasound microbubble destruction-mediated changes in blood-brain barrier permeability assessed by contrast-enhanced magnetic resonance imaging |
| FASANO A, 2017, NEUROLOGY | 10.1212/WNL.0000000000004268 | ARTICLE | NEUROLOGY | 2017 | FASANO, A | UNIV TORONTO, CANADA, CANADA | 33 | 6.6 | 0.592 | Human | Movement disorder | MRI-guided focused ultrasound thalamotomy in non-ET tremor syndromes |
| KIM M, 2017, STERIOT FUNCT NEUROS | 10.1159/000478666 | ARTICLE | STERIOT FUNCT NEUROS | 2017 | CHANG, JW | YONSEI UNIV, SOUTH KOREA | 33 | 6.6 | 0.592 | Human | Movement disorder | Comparative evaluation of magnetic resonance-guided focused ultrasound surgery for essential tremor |
| O'REILLY MA, 2017, THERANOSTICS | 10.7150/thno.20621 | ARTICLE | THERANOSTICS | 2017 | O'REILLY, MA | SUNNYBROOK RES INST, CANADA | 33 | 6.6 | 0.592 | Animal | Blood-brain barrier opening in a natural canine model of aging | Investigation of the safety of focused ultrasound-induced blood-brain barrier opening in a natural canine model of aging |
| WEINTRAUB D, 2017, MOVEMENT DISORD | 10.1002/mds.26599 | REVIEW | MOVEMENT DISORD | 2017 | ELIAS, WJ | UNIV VIRGINIA, USA | 33 | 6.6 | 0.592 | Review | The emerging role of transcranial magnetic resonance imaging–guided focused ultrasound in functional neurosurgery | The emerging role of transcranial magnetic resonance imaging–guided focused ultrasound in functional neurosurgery |
| DOBRACKOWSKI PP, 2014, INTERV NEURORADIOL | 10.15274/inr.2014-10033 | REVIEW | INTERV NEURORADIOL | 2014 | DOBRACKOWSKI, PP | MED UNIV SILESIA, POLAND | 33 | 4.12 | 0.507 | Review | Movement disorder | MR-guided focused ultrasound: a new generation treatment of Parkinson’s disease, essential tremor and neuropathic pain | (Continued) |
| Paper | DOI                  | Article type | Journal Publication year | Corresponding author | University of corresponding author | Total citations | TC per year | Normalized TC | Type of study | Theme of study | Title of article                                                                 |
|-------|---------------------|--------------|--------------------------|----------------------|-----------------------------------|----------------|------------|--------------|---------------|----------------|-----------------------------------------------------------------------------------|
| FISHMAN PS, 2018, MOVEMENT DISORD | 10.1002/mds.27401 | ARTICLE      | MOVEMENT DISORD 2018     | FISHMAN, PS          | UNIV MARYLAND SCH MED, USA         | 32             | 8          | 0.489        | Human Movement disorder | Neurological adverse event profile of magnetic resonance imaging–guided focused ultrasound thalamotomy for essential tremor |
| MONTEITH SJ, 2013, J NEUROSURG   | 10.3171/2012.10.JNS12186 | ARTICLE     | J NEUROSURG 2013        | MONTEITH, S          | UNIV VIRGINIA, USA                 | 32             | 3.56       | 0.248        | Human Pain | Transcranial magnetic resonance–guided focused ultrasound surgery for trigeminal neuralgia: a cadaveric and laboratory feasibility study |
| MOSER D, 2012, NEUROSURG FOCUS   | 10.3171/2011.10.FOCUS11246 | ARTICLE     | NEUROSURG FOCUS 2012    | MOSER, D             | CTR ULTRASOUND FUNCT NEUROSURG, SWITZERLAND | 32             | 3.2        | 0.373        | Human Targetting error | Measurement of targeting accuracy in focused ultrasound functional neurosurgery |
| JUNG NY, 2019, J NEUROSURG      | 10.3171/2018.2.JNS172514 | ARTICLE     | J NEUROSURG 2019        | CHANG, JW            | YONSEI UNIV, SOUTH KOREA           | 31             | 10.33      | 0.589        | Human Movement disorder | The efficacy and limits of magnetic resonance–guided focused ultrasound pallidotomy for Parkinson’s disease: a Phase I clinical trial |
| WANG F, 2012, PLOS ONE          | 10.1371/journal.pone.0052925 | ARTICLE     | PLOS ONE 2012           | CHEN, Y              | PEKING UNIV, PEOPLES R CHINA       | 31             | 3.1        | 0.361        | Animal Blood-brain barrier | Targeted delivery of GDNF through the blood–brain barrier by MRI-guided focused ultrasound |
| PARK YS, 2019, MOVEMENT DISORD  | 10.1002/mds.27637 | ARTICLE      | MOVEMENT DISORD 2019     | CHANG, JW            | YONSEI UNIV, SOUTH KOREA           | 30             | 10         | 0.57         | Human Movement disorder | Four-year follow-up results of magnetic resonance-guided focused ultrasound thalamotomy for essential tremor |
| APPELBOOM G, 2016, NEURO-Oncology | 10.1093/neruonc/nov137 | REVIEW      | NEURO-Oncology 2016      | APPELBOOM, G          | STANFORD MED CTR, USA              | 30             | 5          | 0.283        | Review | Stereotactic modulation of blood-brain barrier permeability to enhance drug delivery |
| KRISHNA V, 2019, NEUROSURGERY   | 10.1093/neruonc/nov1020 | ARTICLE     | NEUROSURGERY 2019       | KRISHNA, V           | OHIO STATE UNIV, USA               | 29             | 9.67       | 0.551        | Human Movement disorder | Prospective tractography-based targeting for improved safety of focused ultrasound thalamotomy |
| MENG Y, 2019, ANN NEUROL        | 10.1002/ana.25604 | ARTICLE      | ANN NEUROL 2019         | LIPSMAN, N            | SUNNYBROOK RES INST, CANADA        | 28             | 9.33       | 0.532        | Human Blood-brain barrier | Glymphatics visualization after focused ultrasound-induced blood-brain barrier opening in humans |
exclusion criteria (Hynynen et al., 2001, 2006; McDannold et al., 2005, 2010; Jordão et al., 2010; Bystritsky et al., 2011; Yoo et al., 2011; Jeamnom et al., 2012; Park et al., 2012; Treat et al., 2012; Fan et al., 2013; Nance et al., 2014; Elias et al., 2016; Kovacs et al., 2017; Mainprize et al., 2019; Alzheimer’s disease in a mouse model: MR imaging-guided focused ultrasound targeted to the hippocampus opens the blood-brain barrier and improves pathologic abnormalities and behavior—PubMed). The included top-cited articles are summarized in Table 1.

These articles can be divided into three topics depending on the pathology type in which MRgFUS use has been described in the article. Equal numbers of articles involved human studies and animal studies (n = 41). Thirty-six studies were related to blood brain barrier (BBB) disruption and only three studies of these were human studies. Twenty-five studies focused on the role of FUS in patients with movement disorders and all were human studies. Three articles discussed the role of FUS in patients with pain, and a similar number of articles discussed the role of FUS for oncological indications in humans. Eleven articles discussed the technical aspects, while one clinical article described the use of FUS in patients with obsessive-compulsive disorders (OCD).

The article that received the maximum number of citations was “Non-invasive MR Imaging–guided Focal Opening of the Blood-Brain Barrier in Rabbits” published in 2001 in Radiology by Hynynen et al. and cited 855 times (Hynynen et al., 2001). The next two articles in the top 100 list, published in the New England Journal of Medicine, described the clinical application of MRgFUS in essential tremors. The first of these, titled “A Pilot Study of Focused Ultrasound Thalamotomy for Essential Tremor,” was a pilot trial that established the safety and efficacy of focused ultrasound thalamotomy in 15 patients suffering from essential tremor (Elias et al., 2013). Another article published in 2016, titled “A Randomized Trial of Focused Ultrasound Thalamotomy for Essential Tremor,” was a multicentre trial that confirmed the efficacy of focused ultrasound thalamotomy (Elias et al., 2016). The total citations per year for this article were 62.67, the maximum out of 100 cited articles.

Main information

These 100 articles were published in 45 journals over 22 years (1998–2019). There were 85 original and 15 review articles. The average number of years from the date of publication was 7.22. Interestingly, most of these articles were published recently: 2017 (15 articles), 2018 (12 articles), and 2014 (10 articles) (Figure 1A).

Average citations per document were 97.78, while average citations per year per document were 12.47 (Table 2). Maximum mean citations per article and mean citations per year were for the articles published in 2001 and were 855 and 42.75, respectively (Figure 1B).
### TABLE 2  Main information about data.

| Description                        | Results          |
|-----------------------------------|------------------|
| Timespan                         | 1998:2019        |
| Sources (Journals, Books, etc.)  | 45               |
| Documents                        | 100              |
| Average years from publication   | 7.22             |
| Average citations per documents  | 97.78            |
| Average citations per year per doc| 12.47            |
| References                       | 2,798            |

### Document types

- Article: 85
- Article; proceedings paper: 1
- Editorial material: 1
- Review: 13

### Document contents

- Keywords Plus (ID): 365
- Author's keywords (DE): 169

### Authors

- Authors: 481
- Author appearances: 833
- Authors of single-authored documents: 0
- Authors of multi-authored documents: 481

### Authors collaboration

- Single-authored documents: 0
- Documents per Author: 0.208
- Authors per document: 4.81
- Co-authors per documents: 8.33
- Collaboration index: 4.81

### Journals

**Figure 1C** shows the top 23 journals that published two or more articles. *Journal of Neurosurgery* had a maximum of 11 publications, followed by the *Journal of Controlled Release* (7), *Movement Disorders* (6 articles), and *Neurosurgery* (6 articles). Other journals that published at least one of these articles included *Stereotactic and Functional Neurosurgery*, the *Journal of Neurology, Neurosurgery and Psychiatry*, and the *Journal of Magnetic Resonance Imaging*.

**Figure 1D** shows the graphical representation of Bradford’s Law, which estimates the exponentially diminishing returns of searching for references in science journals. It shows that the *Journal of Neurosurgery*, *Journal of Controlled Release, Movement Disorders, Neurosurgery and Physics in Medicine and Biology* lie in Zone 1.

**Figure 2A** shows the journal-wise distribution of the total citations received by these articles. The articles published in *Radiology* were cited the most (1,064 citations), followed by *New England Journal of Medicine* (761 citations) and *Journal of Neurosurgery* (736 citations). The articles published in these journals were 4, 2, and 11, respectively. **Figure 2B** shows the journal impact measured in the H-index, with *the Journal of Neurosurgery* at the top. **Figure 2C** shows the source dynamics, i.e., the year-wise increase in the number of articles. *Journal of Neurosurgery* published the first article in 2012, and there has been a rapid increase in the published articles since.

### Authors

These top 100 cited articles included 481 authors who made 833 appearances in these 100 articles. The number of co-authors per document was 8.33, with a collaboration index of 4.81. None of these articles were published by a single author.

**Figure 2D** shows the top 20 authors who published the maximum number of these articles. Hynynen K authored 28 out of these top 100, followed by Elias WJ (15 articles) and Zadicario (12 articles). **Supplementary Figure 1** shows the top 20 authors’ production over time, with the size of the dots denoting the number of articles and the shade of the dots denoting the number of citations per year. **Figure 3A** shows the graphical representation of Lotka’s law, which denotes the distribution of the number of articles published by the number of authors. Most of the authors (85%) published 1 (70%) or 2 (15%) articles. **Figure 3B** shows the authors whose articles received the maximum number of citations. Articles authored by Hynynen received the maximum number of citations (4130). **Table 3** shows the various indexes of the top 50 authors. H-index and g-index were maximum for Hynynen K, while the m-index, which considers the h-index and the number of years an author has been active for, was maximum for Chang JW (1.5710).

### Affiliations and country

**Figure 4A** shows the top 20 universities which published the maximum number of articles. The maximum number of authors belong to the University of Toronto. Most universities were from the United States, Canada, Israel, and Taiwan.

These top 100 cited articles were authored by corresponding authors from 11 countries, showing the limited availability of this technology. **Figure 4B** shows the country-wise distribution of the corresponding authors of these top 100 cited articles, with the maximum number of articles (n = 45) published from the United States. It was followed by Canada (19 articles) and China (10 articles). There were significant international collaborations in these articles, as shown by the orange bars in **Figure 4B**. The MCP ratio (Multicountry production ratio, which is the ratio of articles authored by authors belonging to more than one country to those authored by authors from one single country) was maximum (= 1) for the articles published by the authors from Switzerland and Finland, suggesting that all their articles had multicountry collaborations. Even the articles published
from the United States had an MCP ratio of 0.31, with 14 out of 45 articles having authors from countries other than the United States. Figure 5A shows the world map with different shades of blue, showing the countries of all the authors (not corresponding authors alone) who were part of the author list of these 100 articles. It shows that most of the authors belonged to North America and Europe. Figure 5B shows the number of times the articles from a given country (as per the corresponding author) were cited. The articles from the United States were cited 5,125 times, followed by Canada (1,814 citations) and China (852 citations). However, average citations per article were maximum for the articles published from Switzerland (142), followed by the articles from the United States (113.9).

Figure 6A shows the number of times these top 20 cited articles were cited in all the journals, with the article by Hynynen et al. published in Radiology in 2011 cited 855 times. Figure 6B shows the number of times these top 100 cited articles were cited in these top 100 cited articles. Article by Hynynen et al. published in Radiology in 2011 was cited in 40 out of these top 100 cited articles.

Supplementary Figure 2 shows the most commonly used keywords in these top 100 cited articles. The most common keyword was “focused ultrasound,” followed by “blood-brain barrier” and “essential tremor.”

Supplementary Figure 3 shows the three-field plot between the author country (left field), author (center field), and the keywords (right field). It can be appreciated that the countries with a maximum number of connections were Canada and the United States of America (USA). In contrast, the authors with the maximum number of connections were Hynynen K, Lozano AM, Lipsman N, and Elias WJ.

**Discussion**

MRgFUS is one of the most evolving fields in the neurosurgery. This scientometric analysis of the MRgFUS revealed some interesting and intriguing trends. First, these articles were published over the last 22 years, from 1998 to 2019. Obviously, it takes a few years for any article to garner many citations to feature in the top 100 cited articles and more importantly adoption in the clinical field given novelty of the technology. However, articles published recently, as recent as in 2019, appeared in this top 100 list. This reflects the rapid evolution and the acceptance of the field, not only by clinician but also the patients. As this technology is evolving and explored in newer neuropsychiatric indications, the scientific publications and their citations are going to be more voluminous and robust in near future.

Secondly, only 11 countries contributed to these top 100 cited articles, with the top 2 countries (the United States and Canada) contributing to more than half of these articles. As MRgFUS is a new technology and its availability is yet limited. There was no article from low to middle-income countries,
perhaps due to the high cost of initial set up. The low acceptance of a surgical procedure for non-life-threatening diseases may also contribute to the limited interest of many countries. Although the average citations per document of these articles were less when compared with the top 100 cited articles on other pathologies, the average citations per document per year were higher (Agrawal et al., 2021). This reflects not only that most of these articles were published recently but also that they are being increasingly cited and applied increasingly to clinical and translational research.

The analysis revealed that 41 articles were based on animal or cadaveric studies to study the preclinical aspects of focused ultrasound. It again reflects the novelty of the technology and value of translational impact in clinical neurosurgery. Amongst the human studies, most of the articles (n = 25) described the use of MRgFUS in various movement disorders, with essential tremor being the commonest pathology. The other rare pathologies where the use of MRgFUS has been described in these studies are Parkinson’s disease, dystonia, and OCD.
| Element                | H Index | G Index | M Index  | Total citations | Number of articles | Production year start |
|------------------------|---------|---------|----------|-----------------|-------------------|----------------------|
| HYNYNEN K              | 28      | 28      | 1.167    | 4,130           | 28                | 1998                 |
| ELIAS WJ               | 15      | 15      | 1.5      | 1,426           | 15                | 2012                 |
| ZADICARIO E            | 12      | 12      | 0.75     | 1,460           | 12                | 2006                 |
| CHANG JW               | 11      | 11      | 1.571    | 918             | 11                | 2015                 |
| LIPSMAN N              | 10      | 10      | 1.111    | 1,298           | 10                | 2013                 |
| MCDANNOLD N            | 10      | 10      | 0.476    | 2,318           | 10                | 2001                 |
| WINTERMARK M           | 10      | 10      | 0.5      | 1,331           | 10                | 2012                 |
| JOLESZ FA              | 8       | 8       | 0.333    | 1,853           | 8                 | 1998                 |
| HUANG YX               | 7       | 7       | 0.583    | 1,012           | 7                 | 2010                 |
| LOZANO AM              | 7       | 7       | 0.778    | 962             | 7                 | 2013                 |
| VYKHODTSEVA N          | 7       | 7       | 0.333    | 1,765           | 7                 | 2001                 |
| AUBERT I               | 6       | 6       | 0.5      | 731             | 6                 | 2010                 |
| CHANG WS               | 6       | 6       | 0.857    | 394             | 6                 | 2015                 |
| JUNG HH                | 6       | 6       | 0.857    | 394             | 6                 | 2015                 |
| LIU HL                 | 6       | 6       | 0.5      | 653             | 6                 | 2010                 |
| SHAH BB                | 6       | 6       | 0.667    | 1,000           | 6                 | 2013                 |
| EAMES M                | 5       | 5       | 0.5      | 239             | 5                 | 2012                 |
| GHANOUNI P             | 5       | 5       | 0.714    | 572             | 5                 | 2015                 |
| KASSELL NF             | 5       | 5       | 0.385    | 252             | 5                 | 2009                 |
| MEDEL R                | 5       | 5       | 0.385    | 252             | 5                 | 2009                 |
| O’REILLY MA            | 5       | 5       | 0.625    | 247             | 5                 | 2014                 |
| SCHWARTZ ML            | 5       | 5       | 0.556    | 493             | 5                 | 2013                 |
| SNELL J                | 5       | 5       | 0.5      | 239             | 5                 | 2012                 |
| YEH CK                 | 5       | 5       | 0.556    | 371             | 5                 | 2013                 |
| AUBRY JF               | 4       | 4       | 0.333    | 238             | 4                 | 2010                 |
| FAN CH                 | 4       | 4       | 0.444    | 320             | 4                 | 2013                 |
| GWINN R                | 4       | 4       | 0.667    | 550             | 4                 | 2016                 |
| HANES J                | 4       | 4       | 0.5      | 310             | 4                 | 2014                 |
| HUSS DS                | 4       | 4       | 0.5      | 247             | 4                 | 2014                 |
| KONOFAVOUR EE          | 4       | 4       | 0.333    | 231             | 4                 | 2010                 |
| MENG Y                 | 4       | 4       | 1        | 439             | 4                 | 2018                 |
| MONTEITH SJ            | 4       | 4       | 0.4      | 494             | 4                 | 2012                 |
| PRICE RJ               | 4       | 4       | 0.5      | 310             | 4                 | 2014                 |
| SHEEHAN JP             | 4       | 4       | 0.308    | 196             | 4                 | 2009                 |
| WANG F                 | 4       | 4       | 0.308    | 199             | 4                 | 2009                 |
| WERNER B               | 4       | 4       | 0.308    | 575             | 4                 | 2009                 |
| ZHANG YZ               | 4       | 4       | 0.364    | 623             | 4                 | 2011                 |
| BLACK SE               | 3       | 3       | 0.75     | 310             | 3                 | 2018                 |
| BOCH AL                | 3       | 3       | 0.25     | 187             | 3                 | 2010                 |
| CHENG Y                | 3       | 3       | 0.231    | 168             | 3                 | 2009                 |
| DALLAPIZZA RF          | 3       | 3       | 0.429    | 523             | 3                 | 2015                 |
| EISENBERG HM           | 3       | 3       | 0.5      | 463             | 3                 | 2016                 |
| FINK M                 | 3       | 3       | 0.25     | 187             | 3                 | 2010                 |
| FISHMAN PS             | 3       | 3       | 0.5      | 463             | 3                 | 2016                 |
| HARNOF S               | 3       | 3       | 0.188    | 206             | 3                 | 2006                 |
| HEYN C                 | 3       | 3       | 0.75     | 411             | 3                 | 2018                 |
| JEANNDENN D            | 3       | 3       | 0.231    | 513             | 3                 | 2009                 |
| JUNG NY                | 3       | 3       | 0.6      | 94              | 3                 | 2017                 |
| KLIBANOV AL            | 3       | 3       | 0.375    | 264             | 3                 | 2014                 |
| KRISHNA V              | 3       | 3       | 0.75     | 124             | 3                 | 2018                 |
There was one animal study and four human trials in the top five cited articles (Hynynen et al., 2001; McDannold et al., 2010; Elias et al., 2013, 2016; Lipsman et al., 2014). The highest cited article was an animal study. Hynynen et al. studied if focused ultrasound beams can be used to locally open the blood-brain barrier without damage to surrounding brain tissue and if magnetic resonance (MR) imaging can be used to monitor this procedure in this article (Hynynen et al., 2001). The authors established that the BBB could be consistently opened with transcranial FUS, opening a new translational field in neurological disorders.

Three out of four human trials were proof of concept studies or pilot studies (McDannold et al., 2010; Elias et al., 2013, 2016). The second most cited article was a pilot study by Elias et al. and published in *NEJM* in 2013 (Elias et al., 2013). The authors reported total tremor and disability scores improved from 54.9 to 24.3 ($P = 0.001$) and 18.2 to 2.8 ($P = 0.001$), respectively in 15 ET patients treated with FUS thalamotomy. This pilot trial was followed by a multicentric randomized controlled trial, published in *NEJM* in 2016, comparing the efficacy of unilateral focused ultrasound thalamotomy with a sham procedure in 76 patients with ET (Elias et al., 2016). The authors observed that hand-tremor scores improved more after focused ultrasound
thalamotomy than after sham procedure, and the improvement was maintained 12 months after thalamotomy. Improvement in secondary outcome measures assessing disability and quality of life was also noticed.

These 100 top cited articles were published in in 45 various neurosurgical, neurological, radiological, and basic sciences research journals, including high-impact journals like *NEJM*, *JAMA Neurology*, *Nature communications*, *Annals of Neurology*, *Movement Disorders*, *Radiology*, and *Neurosurgery*. This diversity may represent the interest from different specialties, leading to faster advancements in this technology and a steep increase in the amount of literature. *Journal of Neurosurgery* published 11 out of these top 100, perhaps related to the fact that neurosurgeons are the end users of this technology and have been actively involved in FUS-related research.

The top-cited article by Hynynen guided *Radiology* to be the maximally cited journal out of all the journals in which these articles were published (*Hynynen et al., 2001*).

One of the important finding noted in this study was that the number of co-authors per document was 8.33, indicating that these articles were published by research...
teams with larger collaborative members and/or multicentric collaboration. Moreover, 15% of the authors contributed to more than two articles in the top 100 cited articles. Hynynen K, a Professor of Medical Biophysics at the University of Toronto, was the top contributor in these journals, contributing to 28 out of these top 100 cited articles, followed by Elias WJ (15 articles) and Zadicario (12 articles). The second highest contributor to these articles is Elias WJ, a Professor of Neurological Surgery at the University of Virginia. The third highest contributor was Eyal Zadicario, who is a part of the InSightec (manufacturer) team. Hynynen K has contributed to FUS research for more than three decades and is the lead author of the highly cited article in this list.

**Limitations**

There are some inherent drawbacks of bibliometric analysis. The reasons why a paper is cited multiple times may be diverse and may not accurately reflect the influence of the study in question (Garfield, 1979). Sole reliance on these indicators can lead to missing specific papers reporting (Allen et al., 2009). Similarly, recent publications on the topic and young researchers might not have accrued enough citations to make it to the list of top 100 articles. One of the inherent limitation of this study is that the search criteria included both the animal and human studies. It is not uncommon to have lesser citation of the animal studies than human studies, given recent and increasingly more acceptance in clinical trials and clinical
practise. The citation matrix alone should not be taken as the sole criteria about the value and rigor of the study. The search was conducted on Web of Science, the most common database used for bibliometric analyses, but still, fallacious exclusions of some articles could have happened due to the keyword-specific results obtained.

**Conclusion**

MRgFUS is one of the fastest evolving field in neurosurgery, specifically functional neurosurgery with increasing studies in recent years. As novel indications are studied, it is crucial to identify the most important topics and contributors to the field as scientific literature expands to guide clinician and research in the field. Most of the top 100 cited articles comes from North America and Europe, with the United States and Canada contributing to more than half of the articles on MRgFUS. The top 100 cited articles also highlight the access of MRgFUS to developed countries and healthcare disparity in access of MrgFUS to developing countries.

**Author contributions**

KG: conceptualization, methodology, software, writing, rewriting and editing, data curation, writing—original draft preparation, visualization, investigation, software, and validation. MR: conceptualization, writing, rewriting and editing, writing—original draft preparation, visualization, investigation, supervision, software, and validation. VK: conceptualization, methodology, rewriting and editing, and supervision. MS and AR: methodology, rewriting and editing, and supervision. All authors contributed to the article and approved the submitted version.

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**Conflict of interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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**Supplementary material**

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2022.981571/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Graph showing the year wise distribution of number of articles among the top 100 cited articles on MRgFUS published by different authors and the number of citations received by articles published in different years.

SUPPLEMENTARY FIGURE 2
Graph showing most frequently used keywords in the top 100 cited articles on MRgFUS.

SUPPLEMENTARY FIGURE 3
Three fields plot showing the predominant countries, surgeons and the key areas of work from the top 100 cited articles on MRgFUS.
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