Bibliometric analysis of the top-100 most cited articles on the radiosurgical management of cerebral arteriovenous malformation

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INTRODUCTION

Cerebral arteriovenous malformations (AVMs) are vascular lesions characterized by a pathological connection between the venous and arterial circulation through a nidus.⁴ These lesions can be diagnosed in the pediatric and adult populations, with an incidence rate of 1 person per 100,000 and a point prevalence of 18 persons per 100,000.¹³
The treatment option for accessible AVMs is usually achieved by complete surgical resection.\[^5\] On the contrary, inaccessible deep-seated lesions and AVMs situated in eloquent cortices are commonly managed non-surgically.\[^4,5\] One of the alternative and effective methods of managing patients with AVMs is radiosurgery, especially lesions of small and moderate sizes.\[^4,5,7\]

Radiosurgery is defined as “The localized, focused, high-dose, irradiation commonly performed using Gamma knife (Leksell Gamma Knife® Perfexion, Elekta, Stockholm, Sweden), CyberKnife (Accuray Incorporated, 1310 Chesapeake Terrace, Sunnyvale, CA 94089, USA), or linear accelerator (LINAC).”\[^5\] Radiosurgery aims to irradiate the lesion by obliterating the abnormal blood vessels of the AVM nidus, without compromising the normal brain parenchyma.\[^5\] The clinical effectiveness of radiosurgery is commonly assessed by measuring the obliteration of the pathological blood vessels on angiography.\[^5\] However, some lesions can become angio-occult that can be apparent only on magnetic resonance imaging. Therefore, angiographic obliteration alone cannot serve to assess the effectiveness of radiosurgery in AVMs.\[^5\] The application of radiosurgery has yielded acceptable and affordable risk-to-benefit in the management of unruptured/partially-resected AVMs, or during staged or partial embolization.\[^7,8\]

Bibliometric analyses serve to address the top-cited articles in a discipline-specific scientific topic.\[^18\] In addition, certain areas of research requiring further development can be identified and addressed accordingly.\[^18\] Bibliometric analyses have been performed in several neurosurgical disciplines, including peripheral, traumatic, oncology, spine, and vascular-related topics.\[^1,2,6,12,16,18\]

Considering the growing field of radiosurgery and its application in the management of AVMs, it is paramount to perform a bibliometric analysis of the most-influential articles in the literature. The main aim of the study is to identify, analyze, and report the current knowledge of the top-100 most-cited articles on the radiosurgical management of cerebral AVMs.

**MATERIALS AND METHODS**

The identification of the most-cited articles on the radiosurgical management of AVM in the Scopus database was accessed in July 2020. The title-specific search using “arteriovenous malformation” as a search keyword was conducted. The outcome of the search was rearranged based on the article's citations count in descending order. The acquisition of the top-100 articles discussing the radiosurgical management was selected after fulfilling our inclusion and exclusion criteria. Articles discussing the radiosurgical management of cerebral AVM as a primary outcome were included. Spinal or non-intracranial AVM, conference papers, and non-English articles predominantly discussing the endovascular or microsurgical management were excluded from the study.

The examined top-100 most cited articles were categorized into the following four entities: (1) clinical, (2) gamma knife radiosurgery, (3) linear accelerator (LINAC) radiosurgery, and (4) proton beam radiosurgery. In the performance of this bibliometric review, the following citometric relevant parameters were collected; article title, authors, 1st author's specialty, contributing institutions, journals, country of origin, year of publication, citation count (CC), Citation per year (CY), Hirsch index (H-Index), Journal's Source Normalized Impact Per Paper, Journal's SCImago Journal Rank, and Journal Impact Factor.

The present study does not involve human subjects. Therefore, it is exempted from ethical approval, giving the nature of the study being non-interventional.

**RESULTS**

The keyword-based literature review resulted in identifying 9939 articles discussing AVM and, of which the top-100 articles according to the inclusion criteria were examined [Table 1].

The top-100 articles on the radiosurgical management of AVM were published between 1972 and 2016 [Figure 1].

**Figure 1:** Publication trends for the top-100 most cited articles on the radiosurgical management of arteriovenous malformation (1972–2016).
Table 1: The top-100 most cited articles on the radiosurgical management of arteriovenous malformation.

| Rank | Authors                  | Title                                                                 | Journal                                      | CC | CY  |
|------|--------------------------|----------------------------------------------------------------------|----------------------------------------------|----|-----|
| 1st  | Lunsford et al., 1991    | Stereotactic radiosurgery for arteriovenous malformations of the brain | Journal of Neurosurgery                       | 520| 17.9|
| 2nd  | Steiner et al., 1992     | Clinical outcome of radiosurgery for cerebral arteriovenous malformations | Journal of Neurosurgery                       | 459| 16.4|
| 3rd  | Kjellberg et al., 1983   | Bragg-Peak Proton-Beam Therapy for Arteriovenous Malformations of the Brain | New England Journal of Medicine              | 388| 10.5|
| 4th  | Gobin et al., 1996       | Treatment of brain arteriovenous malformations by embolization and radiosurgery | Journal of Neurosurgery                       | 299| 12.5|
| 5th  | Colombo et al., 1994     | Linear accelerator radiosurgery of cerebral arteriovenous malformations: an update | Neurosurgery                                  | 281| 10.8|
| 6th  | Pollock, et al., 1998    | Factors associated with successful arteriovenous malformation radiosurgery | Neurosurgery                                  | 271| 12.3|
| 7th  | Flickinger, et al., 2000 | Development of a model to predict permanent symptomatic post radiosurgery injury for arteriovenous malformation patients | International Journal of Radiation Oncology Biology Physics | 251| 12.6|
| 8th  | Friedman, et al., 1995   | Linear accelerator radiosurgery for arteriovenous malformations: the relationship of size to outcome | Journal of Neurosurgery                       | 247| 9.9 |
| 9th  | Flickinger, et al., 1996 | A dose-response analysis of arteriovenous malformation obliteration after radiosurgery | International Journal of Radiation Oncology Biology Physics | 243| 10.1|
| 10th | Maruyama et al., 2005    | The risk of hemorrhage after radiosurgery for cerebral arteriovenous malformations | New England Journal of Medicine               | 235| 15.7|
| 11th | Schneider et al., 1997   | Histopathology of arteriovenous malformations after gamma knife radiosurgery | Journal of Neurosurgery                       | 232| 10.1|
| 12th | Pollock and Flickinger, 2002 | A proposed radiosurgery-based grading system for arteriovenous malformations | Journal of Neurosurgery                       | 227| 12.6|
| 13th | Steinberg et al., 1990   | Stereotactic heavy-charged-particle bragg peak radiation for intracranial arteriovenous malformations | New England Journal of Medicine               | 224| 7.5 |
| 14th | Pollock et al., 1996     | Hemorrhage risk after stereotactic radiosurgery of cerebral arteriovenous malformations | Neurosurgery                                  | 218| 9.1 |
| 15th | Betti et al., 1989       | Stereotactic radiosurgery with the linear accelerator: treatment of arteriovenous malformations | Neurosurgery                                  | 213| 6.9 |
| 16th | Karlsson et al., 1997    | Prediction of obliteration after gamma knife surgery for cerebral arteriovenous malformations | Neurosurgery                                  | 208| 9.0 |
| 17th | Flickinger et al., 1997  | Complications from arteriovenous malformation radiosurgery: multivariate analysis and risk modeling | International Journal of Radiation Oncology Biology Physics | 200| 8.7 |
| 18th | Yamamoto et al., 1996    | Gamma knife radiosurgery for arteriovenous malformations: long-term follow-up results focusing on complications occurring more than 5 years after irradiation | Neurosurgery                                  | 180| 7.5 |
| 19th | Steiner, et al., 1972    | Stereotactic radiosurgery for cerebral arteriovenous malformations. Report of a case. | Acta Chirurgica Scandinavica Radiotherapy and Oncology | 176| 3.7 |
| 20th | Flickinger et al., 2002  | An analysis of the dose-response for arteriovenous malformation radiosurgery and other factors affecting obliteration | Acta Chirurgica Scandinavica Radiotherapy and Oncology | 174| 9.7 |
| 21st | Friedman et al., 1996    | The risk of hemorrhage after radiosurgery for arteriovenous malformations | Journal of Neurosurgery                       | 174| 7.3 |
| 22nd | Flickinger et al., 1999  | A multi-institutional analysis of complication outcomes after arteriovenous malformation radiosurgery | International Journal of Radiation Oncology Biology Physics | 158| 7.5 |
| 23rd | Friedman and Bova, 1992  | Linear accelerator radiosurgery for arteriovenous malformations | Journal of Neurosurgery                       | 158| 5.6 |
| 24th | Pollock et al., 2003     | Patient outcomes after arteriovenous malformation radiosurgical management: results based on a 5–14-year follow-up study | Neurosurgery                                  | 157| 9.2 |

(Contd...)
| Rank | Authors                  | Title                                                                 | Journal                                                                 |
|------|--------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------|
| 25th | Andrade-Souza et al., 2007 | Embolization before radiosurgery reduces the obliteration rate of arteriovenous malformations | Neurosurgery                                                              |
| 26th | Miyawaki et al., 1999    | Five year results of LINAC radiosurgery for arteriovenous malformations: outcome for large AVMS | International Journal of Radiation Oncology Biology Physics |
| 27th | Colombo et al., 1989     | Linear accelerator radiosurgery of cerebral arteriovenous malformations | Neurosurgery                                                              |
| 28th | Starke et al., 2013      | A practical grading scale for predicting outcome after radiosurgery for arteriovenous malformations: analysis of 1012 treated patients | Journal of Neurosurgery                                                  |
| 29th | Pollock et al., 2008     | Modification of the radiosurgery-based arteriovenous malformation grading system | Neurosurgery                                                              |
| 30th | Pollock et al., 1996     | Repeat stereotactic radiosurgery of arteriovenous malformations: factors associated with incomplete obliteration | Neurosurgery                                                              |
| 31st | Pollock et al., 1994     | Patient outcomes after stereotactic radiosurgery for 'operable' arteriovenous malformations | Neurosurgery                                                              |
| 32nd | Schlienger et al., 2000  | Linac radiosurgery for cerebral arteriovenous malformations: results in 169 patients | International Journal of Radiation Oncology Biology Physics |
| 33rd | Flickinger et al., 1992  | Radiosurgery and brain tolerance: an analysis of neurodiagnostic imaging changes after gamma knife radiosurgery for arteriovenous malformations | International Journal of Radiation Oncology Biology Physics |
| 34th | Friedman et al., 2003    | Analysis of factors predictive of success or complications in arteriovenous malformation radiosurgery | Neurosurgery                                                              |
| 35th | Lewis et al., 1994       | Management of tentorial dural arteriovenous malformations: transarterial embolization combined with stereotactic radiation or surgery | Journal of Neurosurgery                                                  |
| 36th | Pan et al., 2000         | Gamma knife radiosurgery as a single treatment modality for large cerebral arteriovenous malformations | Journal of Neurosurgery                                                  |
| 37th | Pollock et al., 2004     | Radiosurgery for arteriovenous malformations of the basal ganglia, thalamus, and brainstem | Journal of Neurosurgery                                                  |
| 38th | Loeffler et al., 1989    | Stereotactic radiosurgery for intracranial arteriovenous malformations using a standard linear accelerator | International Journal of Radiation Oncology Biology Physics |
| 39th | Karlsson et al., 2001    | Risk for hemorrhage during the 2-year latency period following gamma knife radiosurgery for arteriovenous malformations | International Journal of Radiation Oncology Biology Physics |
| 40th | Fabrikant et al., 1984   | Stereotactic heavy-ion Bragg peak radiosurgery for intracranial vascular disorders: method for treatment of deep arteriovenous malformations | British Journal of Radiology                                             |
| 41st | Liščák et al., 2007     | Arteriovenous malformations after Leksell gamma knife radiosurgery: rate of obliteration and complications | Neurosurgery                                                              |
| 42nd | Sirin et al., 2006       | Prospective staged volume radiosurgery for large arteriovenous malformations: indications and outcomes in otherwise untreatable patients | Neurosurgery                                                              |
| 43rd | Lindqvist et al., 2000   | Angiographic long-term follow-up data for arteriovenous malformations previously proven to be obliterated after gamma knife radiosurgery | Neurosurgery                                                              |
| 44th | Ellis et al., 1998       | Analysis of treatment failure after radiosurgery for arteriovenous malformations | Journal of Neurosurgery                                                  |
| 45th | Sasaki et al., 1998      | Arteriovenous malformations in the basal ganglia and thalamus: management and results in 101 cases | Journal of Neurosurgery                                                  |
Table 1: (Continued)

| Rank  | Authors          | Title                                                                 | Journal                          | CC  | CY  |
|-------|------------------|----------------------------------------------------------------------|----------------------------------|-----|-----|
| 46th  | Kano et al., 2012| Stereotactic radiosurgery for arteriovenous malformations, Part 1: management of Spetzler-Martin Grades I and II arteriovenous malformations: clinical article | Journal of Neurosurgery          | 103 | 12.9|
| 47th  | Flickinger et al., 1998| Analysis of neurological sequelae from radiosurgery of arteriovenous malformations: how location affects outcome | International Journal of Radiation Oncology Biology Physics | 102 | 4.6 |
| 48th  | Yamamoto et al., 1992| Long-term results of radiosurgery for arteriovenous malformation: neurodiagnostic imaging and histological studies of angiographically confirmed nidus obliteration | Surgical Neurology                | 102 | 3.6 |
| 49th  | Steinberg et al., 1996| Surgical resection of large incompletely treated intracranial arteriovenous malformations following stereotactic radiosurgery | Journal of Neurosurgery          | 101 | 4.2 |
| 50th  | Wegner et al., 2011| A modified radiosurgery-based arteriovenous malformation grading scale and its correlation with outcomes | International Journal of Radiation Oncology Biology Physics | 100 | 11.1|
| 51st  | Ding et al., 2013| Radiosurgery for patients with unruptured intracranial arteriovenous malformations: clinical article | Journal of Neurosurgery          | 99  | 14.1|
| 52nd  | Kano et al., 2012| Stereotactic radiosurgery for arteriovenous malformations, Part 6: multistaged volumetric management of large arteriovenous malformations: clinical article | Journal of Neurosurgery          | 99  | 12.4|
| 53rd  | Levy et al., 2000| Radiosurgery for childhood intracranial arteriovenous malformations | Neurosurgery                      | 98  | 4.9 |
| 54th  | Karlsson et al., 1997| Factors influencing the risk for complications following Gamma Knife radiosurgery of cerebral arteriovenous malformations | Radiotherapy and Oncology         | 98  | 4.3 |
| 55th  | Engenhart et al., 1994| The role of high-dose, single-fraction irradiation in small and large intracranial arteriovenous malformations | International Journal of Radiation Oncology Biology Physics | 97  | 3.7 |
| 56th  | Shin et al., 2002| Retrospective analysis of a 10-year experience of stereotactic radiosurgery for arteriovenous malformations in children and adolescents | Journal of Neurosurgery          | 96  | 5.3 |
| 57th  | Ogilvy, 1990| Radiation therapy for arteriovenous malformations: a review | Neurosurgery                      | 93  | 3.1 |
| 58th  | Izawa et al., 2005| Long-term complications after gamma knife surgery for arteriovenous malformations | Journal of Neurosurgery          | 92  | 6.1 |
| 59th  | Levy et al., 1989| Stereotactic heavy-charged-particle brag peak radiosurgery for the treatment of intracranial arteriovenous malformations in childhood and adolescence | Neurosurgery                      | 92  | 3.0 |
| 60th  | Maruyama et al., 2004| Stereotactic radiosurgery for brainstem arteriovenous malformations: factors affecting outcome | Journal of Neurosurgery          | 91  | 5.7 |
| 61st  | Pollock et al., 2000| The rationale and technique of staged-volume arteriovenous malformation radiosurgery | International Journal of Radiation Oncology Biology Physics | 91  | 4.6 |
| 62nd  | Lax and Karlsson, 1996| Prediction of complications in gamma knife radiosurgery of arteriovenous malformations | Acta Oncologica                    | 91  | 3.8 |
| 63rd  | Mathis et al., 1995| The efficacy of particulate embolization combined with stereotactic radiosurgery for treatment of large arteriovenous malformations of the brain | American Journal of Neuroradiology | 90  | 3.6 |
| 64th  | Dawson et al., 1990| Treatment of arteriovenous malformations of the brain with combined embolization and stereotactic radiosurgery: results after 1 and 2 years | American Journal of Neuroradiology | 90  | 3.0 |
| 65th  | Heikkenen et al., 1989| Relief of epilepsy by radiosurgery of cerebral arteriovenous malformations | Stereotactic and Functional Neurosurgery | 89  | 2.9 |

(Contd...)
| Rank | Authors                  | Title                                                                 | Journal                                      | CC | CY |
|------|--------------------------|----------------------------------------------------------------------|----------------------------------------------|----|----|
| 66th | Maesawa et al., 2000     | Repeated radiosurgery for incompletely obliterated arteriovenous malformations | Journal of Neurosurgery                        | 88 | 4.4|
| 67th | Shin et al., 2004        | Analysis of nidus obliteration rates after gamma knife surgery for arteriovenous malformations based on long-term follow-up data: The University of Tokyo experience | Journal of Neurosurgery                        | 87 | 5.4|
| 68th | Chang et al., 1997       | Stereotactic radiosurgery of arteriovenous malformations: pathologic changes in resected tissue | Clinical Neuropathology                       | 87 | 3.8|
| 69th | Deruty et al., 1993      | The combined management of cerebral arteriovenous malformations experience with 100 cases and review of the literature | Acta Neurochirurgica                          | 87 | 3.2|
| 70th | Kano et al., 2012        | Stereotactic radiosurgery for arteriovenous malformations after embolization: a case–control study. Clinical article | Journal of Neurosurgery                        | 86 | 10.8|
| 71st | Kano et al., 2012        | Stereotactic radiosurgery for arteriovenous malformations, Part 3: outcome predictors and risks after repeat radiosurgery: clinical article | Journal of Neurosurgery                        | 85 | 10.6|
| 72nd | Yamamoto et al., 1998    | Radiation-related adverse effects observed on neuro-imaging several years after radiosurgery for cerebral arteriovenous malformations | Surgical Neurology                            | 85 | 3.9|
| 73rd | Smyth et al., 2002       | Stereotactic radiosurgery for pediatric intracranial arteriovenous malformations: The University of California at San Francisco experience | Journal of Neurosurgery                        | 82 | 4.6|
| 74th | Chang et al., 2000       | Factors related to complete occlusion of arteriovenous malformations after gamma knife radiosurgery | Journal of Neurosurgery                        | 81 | 4.1|
| 75th | Gallina et al., 1998     | Failure in radiosurgery treatment of cerebral arteriovenous malformations | Neurosurgery                                  | 79 | 3.6|
| 76th | Kihlström et al., 1997   | Magnetic resonance imaging of obliterated arteriovenous malformations up to 23 years after radiosurgery | Journal of Neurosurgery                        | 79 | 3.4|
| 77th | Kurita et al., 2000      | Results of radiosurgery for brain stem arteriovenous malformations | Journal of Neurology, Neurosurgery, and Psychiatry | 78 | 3.9|
| 78th | Karlsson et al., 1998    | Gamma knife surgery for previously irradiated arteriovenous malformations | Neurosurgery                                  | 78 | 3.5|
| 79th | Andrade-Souza et al., 2005 | Radiosurgery for basal ganglia, internal capsule, and thalamus arteriovenous malformation: clinical outcome | Neurosurgery                                  | 77 | 5.1|
| 80th | Schad et al., 1992       | Correction of spatial distortion in magnetic resonance angiography for radiosurgical treatment planning of cerebral arteriovenous malformations | Magnetic Resonance Imaging                   | 77 | 2.8|
| 81st | Gerszten et al., 1996    | Seizure outcome in children treated for arteriovenous malformations using gamma knife radiosurgery | Pediatric Neurosurgery                        | 76 | 3.2|
| 82nd | Kjellberg et al., 1983   | Bragg peak proton beam therapy for arteriovenous malformation of the brain. | Clinical Neurosurgery                         | 76 | 2.1|
| 83nd | Schäuble et al., 2004    | Seizure outcomes after stereotactic radiosurgery for cerebral arteriovenous malformations | Neurology                                     | 75 | 4.7|
| 84th | Loeffler et al., 1990    | Role of stereotactic radiosurgery with a linear accelerator in treatment of intracranial arteriovenous malformations and tumors in children | Pediatrics                                    | 74 | 2.5|
| 85th | Kano et al., 2012        | Stereotactic radiosurgery for arteriovenous malformations, Part 2: management of pediatric patients: clinical article | Journal of Neurosurgery: Pediatrics           | 73 | 9.1|
| 86th | Hadjipanayis et al., 2001 | Stereotactic radiosurgery for motor cortex region arteriovenous malformations | Neurosurgery                                  | 73 | 3.8|
| 87th | Kondziolka et al., 1994  | Stereotactic magnetic resonance angiography for targeting in arteriovenous malformation radiosurgery | Neurosurgery                                  | 72 | 2.8|
| 88th | Ding et al., 2014        | Radiosurgery for low-grade intracranial arteriovenous malformations | Journal of Neurosurgery                        | 71 | 11.8|

(Contd...)
Alkhabiry, et al.: Top-100 articles on SRS in AVM

Table 1: (Continued)

| Rank | Authors            | Title                                                                 | Journal                          | CC | CY |
|------|--------------------|----------------------------------------------------------------------|----------------------------------|----|----|
| 89th | Ding et al., 2014  | Radiosurgery for ruptured intracranial arteriovenous malformations: clinical article | Journal of Neurosurgery          | 69 | 11.5 |
| 90th | Moosa et al., 2014 | Volume-staged versus dose-staged radiosurgery outcomes for large intracranial arteriovenous malformations | Neurosurgical Focus              | 67 | 11.2 |
| 91st | Andrade-Souza et al., 2005 | Testing the radiosurgery-based arteriovenous malformation score and the modified Spetzler-Martin grading system to predict radiosurgical outcome | Journal of Neurosurgery          | 67 | 4.5 |
| 92nd | Bollet et al., 2004 | Efficacy and morbidity of arc-therapy radiosurgery for cerebral arteriovenous malformations: a comparison with the natural history | International Journal of Radiation Oncology Biology Physics | 67 | 4.2 |
| 93rd | Kurita et al., 1998  | Control of epilepsy associated with cerebral arteriovenous malformations after radiosurgery | Journal of Neurology Neurosurgery and Psychiatry | 66 | 3.0 |
| 94th | Ding et al., 2016  | Radiosurgery for Cerebral Arteriovenous Malformations in A Randomized Trial of Unruptured Brain Arteriovenous Malformations (ARUBA)-Eligible Patients: a Multicenter Study | Stroke                           | 64 | 16.0 |
| 95th | Chen et al., 2014  | Seizure outcomes following radiosurgery for cerebral arteriovenous malformations | Neurosurgical Focus              | 64 | 10.7 |
| 96th | Chandler et al., 1993 | Successful radiosurgical treatment of a dural arteriovenous malformation: case report | Neurosurgery                      | 64 | 2.4 |
| 97th | Hung-Chuan, et al., 2005 | Late cyst formation following gamma knife surgery of arteriovenous malformations | Journal of Neurosurgery          | 63 | 4.2 |
| 98th | Massager et al., 2000 | Gamma knife radiosurgery for brainstem arteriovenous malformations: preliminary results | Journal of Neurosurgery          | 63 | 3.2 |
| 99th | Meder et al., 1997  | Cerebral arteriovenous malformations: the value of radiologic parameters in predicting response to radiosurgery | American Journal of Neuroradiology | 63 | 2.7 |
| 100th | Altschuler et al., 1989 | Gamma knife radiosurgery for intracranial arteriovenous malformations in childhood and adolescence | Pediatric Neuroscience            | 63 | 2.0 |

AVM: Arteriovenous malformation, CC: Citation count, CY: Citation per year, LINAC: Linear accelerator

Approximately one-third of publications were produced between 1995 and 2000. The Top-100 articles have accumulated 11,456 citations and the rate of self-citation accounted for 12.12%. The average CY for all papers was seven. The most-studied entity was pertinent to the clinical application of Gamma knife radiosurgery in AVM (68%) [Figure 2]. The United States was the most active country in studying the radiosurgical application in AVM [Figure 3].

The University of Pittsburgh was the most prolific by producing 46 articles in the list [Figure 4]. The Journal of Neurosurgery (JNS) published approximately one-third of the most-cited articles in the list [Figure 5]. Examination of authors showed that Lunsford et al. were the top-3 most contributing authors by being involved in 80% of articles in the list with comparable contribution volume [Figure 6].

The top-most cited article based on the citation count was authored by Lunsford et al., published in 1991 by JNS as “Stereotactic radiosurgery for AVMs of the brain,” to which it collected 520 citations over the years and was ranked the 2nd most-cited based on the citation per year.

The top most cited articles based on the citation per year was authored by Starke et al., published in 2013 by the JNS entitled “A practical grading scale for predicting outcome...”
DISCUSSION

Articles addressing the radiosurgical management of AVMs evolved throughout the decades. Publications commenced by targeting the utilization of stereotactic radiosurgery using Gamma knife in the early 1970s. In the 1980s, as a result of the development and advancement of neuroimaging and proton/photon radiation technology, the publication trends shifted toward proton beam and linear accelerator (LINAC) radiosurgery. In addition, the earliest detailed reports on the utilization of proton beam radiosurgery for AVM with the longest follow-up period were published. In the top-100 list, most articles peaked in the publication in the 1990s, comprising 45% of all articles. Those articles were targeting all aspects of the radiosurgical management of AVM including the clinical outcome, Gamma knife, LINAC, and proton beam radiosurgery. In the 21st century, the majority of publications were highlighting the dose-response and clinical outcome predictions, comprising approximately half of the articles in the top-100 list.

The article ranking first in the top-100 list was published in 1991 by Lunsford et al. titled “Stereotactic radiosurgery for arteriovenous malformations of the brain” which received a total of 520 CC and 17.9 CY. The authors investigated 227 patients who underwent stereotactic radiosurgery for cerebral AVM. Their 3-year experience demonstrated that radiosurgery is an important technique for AVM obliteration, especially lesions previously rendered inoperable. The success rate and risks of complications were dependent on location and volume of the AVM.

A year later, the second highest cited article was published by Steiner et al. titled “Clinical outcome of radiosurgery for cerebral arteriovenous malformations” to which it received 459 CC and 16.4 CY. The authors described the long-term neurological outcomes for 247 consecutive patients with AVM treated with Gamma knife. In their cohort,
radiosurgery has proven to obliterate AVMs as evident by angiography, with few side effects. They suggested that complete protection against rebleeding in AVM occurs only after total obliteration of the lesion.\[21\]

**Gamma knife radiosurgery**

Articles predominantly discussing the application of gamma knife radiosurgery peaked in terms of publication from 1972 to 2016. Operable and non-operable AVMs, deep-seated lesions, staging, and the risk of hemorrhage were the areas of interest to authors investigating the radiosurgical aspect of AVM. Gamma knife radiosurgery populated the majority of publications in the top 100 most cited articles on the radiosurgical management of AVM, comprising around two thirds of the articles. In the category of gamma knife radiosurgery, the first utilization of radiosurgery in obliterating AVM was discussed in the literature. Gobin et al. published an article (ranked 4th) titled “Treatment of brain AVMs by embolization and radiosurgery” to which it received 299 CC and 12.5 CY.\[13\] The authors investigated a cohort of 125 patients who underwent embolization before radiosurgery.\[11\] The patients were included in the study as they were either refusing surgery or were labeled poor surgical candidates.\[11\] They concluded that embolization before radiosurgery serves to facilitate irradiation of large-sized AVMs.\[11\] In addition, they demonstrated that the hemorrhagic risk of the residual nidus is similar to the natural history of AVMs of the same size.\[11\] Pollock et al. published an article (ranked 6th) titled “Factors associated with successful arteriovenous malformation radiosurgery” to which it received 271 CC and 12.3 CY.\[17\] The authors proposed a new method to report the clinical outcome of radiosurgery in AVM.\[17\] It comprised the incorporation of the postoperative neurological deficits and angiographic obliteration results of the AVM. Their multivariate analysis proved that younger age, location, AVM volume, and the number of draining veins were associated with a better obliteration rate after radiosurgical treatment in AVMs.\[17\]

**LINAC radiosurgery**

Articles in addressing LINAC radiosurgery had a publication peak between 1989 and 2007. Around one-fifth of the articles in the top 100 most cited publications on the radiosurgical management of AVM were investigating the usage of LINAC radiosurgery. In addition, the earliest reports on the usage of LINAC radiosurgery were published in the late 80s. Around 61% of articles addressing LINAC radiosurgery peaked in publication in the 90s. In the early years of the 21st century, articles have carried out what has been previously published in the literature, with a relatively larger number of cohorts. Colombo et al. published an article (ranked 5th) titled “Linear accelerator radiosurgery of cerebral AVMs: an update” to which it received 281 CC and 10.8 CY.\[14\] The authors aimed to report the risk of bleeding and evaluate their clinical experience in 153 patients with irradiated AVMs.\[14\] In patients with totally-radiated AVMs, the risk of bleeding decreased from 4.8% to 0% after radiosurgery.\[14\] In contrast, the risk of bleeding in partially-radiated AVMs increased from 4% to 10%.\[14\] Friedman et al. published an article (ranked 8th) titled “Linear accelerator radiosurgery for arteriovenous malformations: the relationship of size to outcome” to which it received 247 CC and 9.9 CY.\[10\] The authors investigated the association between the size of AVM and clinical outcome in a cohort of 158 patients.\[10\] Their study findings demonstrated that AVMs of volumes larger than 10 cc could be successfully managed using LINAC radiosurgery.\[10\]

**Proton beam radiosurgery**

In the “proton beam radiosurgery” entity, articles peaked in the publication from 1983 to 1990. During this period, the earliest, most detailed, and longest follow-up data on the application of proton beam radiosurgery were published. In addition, authors discussed the technicality of proton beam radiosurgery, treatment protocols, and the approach to the selection criteria of patients who were rendered fit to undergo such therapy. Kjellberg et al. published an article (ranked 3rd) titled “Bragg-Peak Proton-Beam Therapy for Arteriovenous Malformations of the Brain” to which it received 388 CC ad 10.5 CY.\[13\] The authors investigated the outcome of such a treatment option in patients with AVM.\[13\] They concluded that proton beam radiosurgery appears to be a useful and alternative treatment of choice for patients harboring cranial AVMs not suitable to other treatment modalities.\[13\] Steinberg et al. published an article (ranked 13th) titled “Stereotactic heavy-charged-particle bragg-peak radiation for intracranial arteriovenous malformations” to which it received 224 CC and 7.5 CY.\[20\] The authors presented their experience in terms of the clinical and radiological outcome in a cohort of 86 patients with inaccessible AVMs, and they concluded that heavy-charged particles proved to be effective treatment for inaccessible AVM.\[20\] However, they highlighted two disadvantages of that time technique; small risk of neurological complications and the long time interval of complete obliteration.\[20\]

**Clinical articles**

Articles addressing the clinical entity of the radiosurgical management of AVM were published between 1990 and 2014. During the specified period, articles predominantly investigated predictors of successful obliteration of AVM utilizing radiosurgery. Furthermore, articles comprehensively investigated and compared dose-staged versus volume-staged radiosurgical treatment of AVM in terms of outcome and
complications. Friedman et al. published an article (ranked 34th) titled “Analysis of factors predictive of success or complications in arteriovenous malformation radiosurgery” with 122 CC and 7.2 CY. The authors reviewed the clinical and radiological data in 269 consecutive patients. Their multivariate analysis proved that eloquent location of AVMs and 12-Gy volume was associated with radiation-induced sequelae in radiosurgery. However, radiological success was associated with a lower grade (Spetzler-Martin) and steeper/higher dose gradients. Steinberg et al. published an article (ranked 49th) titled “Surgical resection of large incompletely treated intracranial arteriovenous malformations following stereotactic radiosurgery” with 122 CC and 7.2 CY. They concluded that adjunct pretreatment with radiosurgery, few years before open surgery, serves to treat large-sized AVMs.

The present bibliometric analysis on the radiosurgical management of AVM highlights the following key aspects to practitioners in the field: (1) radiosurgery remains an important technique in managing patients with inoperable AVMs. (2) Complete obliteration of the lesion can be achieved by radiosurgery. (3) The obliteration rate of AVM following radiosurgery can be predicted by several factors including; age, location, volume, and the number of draining veins. (4) Prior embolization of the lesion facilitates the radiosurgical management of large-sized AVMs. (5) LINAC radiosurgery can successfully treat AVMs of relatively larger volumes (>10 cc). (6) Proton beam radiosurgery, in the form of heavy-charged particles, can be utilized to treat inaccessible AVMs. (7) Radiosurgery, before microsurgical resection, may be of use to treat large-sized and complex AVMs.

Limitations

In the current bibliometric analysis, few obstacles need to be acknowledged which may limit the generalizability of the findings. First, the rate of self-citations was encountered in more than one-tenth of the articles. Therefore, self-citations might falsely increase the CC for all published articles. However, this might be caused by the small society of radiosurgery and the limited number of institutions performing such advanced technology early in the history of radiation treatment (1970s). Second, a title-based search in a keyword-fashion might miss some articles published in the literature, and hence, not included in the analysis. Third, as the CC was considered to rank the articles in a descending order, older articles were likely to accumulate a higher number of citations throughout the years. However, the CY was calculated for all articles to balance this limitation. Fourth, only one database was utilized to conduct this bibliometric analysis. Fifth, due to the time; the relatively newer technology (i.e., CyberKnife) did not appear in our list. However, we expect an increasing number of publications relevant to this topic in the near future. Although bibliometric analyses assess the intellectual scholarly work from a quantitative perspective, the present study identified key and influential articles within this relatively growing field in the management of AVM.

CONCLUSION

The radiosurgical management of AVMs evolved significantly throughout the years. Articles addressing the application of Gamma knife radiosurgery were the most frequently published category by neurosurgeons in the field. The top-two most cited articles in the list were both published in the JNS. Identifications of the publication trends serves as a benchmark for gaining evidence-based knowledge for authors investigating various radiosurgical techniques in AVMs.

Declaration of patient consent

Patient’s consent not required as patients identity is not disclosed or compromised.

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Conflicts of interest

There are no conflicts of interest.

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