Review Article

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The 100 most cited articles in the endovascular treatment of brain arteriovenous malformations

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Abstract:

BACKGROUND: The literature base for endovascular treatment of brain arteriovenous malformations (BAVMs) has grown exponentially in recent decades. Bibliometric analysis has been used to identify impactful articles in other medical specialties. The aim of this citation analysis was to identify and characterize the top 100 most cited articles in the field of endovascular BAVM treatment.

METHODS: The top-cited papers were identified by searching selected keywords ("endovascular treatment," "interventional treatment," "brain arteriovenous malformation," "emboliz(s)ation") on the Web of Science platform. The top 100 articles were ranked according to their number of citations. Each article was further evaluated to obtain predefined characteristics including citation(s) per year, year of publication, authorship, journal-title and impact factor, article topics, article type, and level of evidence.

RESULTS: The top 100 most cited articles for endovascular BAVM treatment were published between 1960 and 2014. The total number of citations for these articles ranged from 56 to 471 (median 85.5). Most articles (76%) were published between 1990 and 2009 in three journals (56%), originated in the USA (52%) followed by France (16%). The most common topic related to embolization agents and the majority of articles constituted level IV or V evidence.

CONCLUSIONS: This study provides a comprehensive overview of the most cited articles in the field of endovascular BAVM treatment. Our analysis recognizes key contributions from authors and institutions in the field and leads to a better understanding of the evidentiary framework for BAVM treatment.

Keywords:

Brain arteriovenous malformation, citation analysis, embolization, endovascular treatment, interventional radiology

Introduction

Brain arteriovenous malformations (BAVMs) are estimated to have a population prevalence of 10–18 per 100,000 adults with a new detection rate of around 1.3/100,000-person years.[1] The natural history of BAVMs remains incompletely understood. While it represents a relatively uncommon disease, it is one of the major causes of intracranial hemorrhage in young people. Current treatment options for BAVMs are complex and may involve surgery, endovascular therapy, and radiosurgery or a combination of modalities.

Endovascular therapies for BAVMs have rapidly evolved in recent decades and this is reflected by the large volume of literature published in this field. This exponential growth of literature can result in difficulties

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in assessing and acknowledging the significance of seminal studies that have led to major advancements in the field. Therefore, there is a need for a comprehensive literature analysis to identify articles with the most impact within this field.

A bibliometric analysis is a simple quantitative technique which provides insight into the citation trends and impact of articles published in a research field. Citation analysis, as a common form of bibliometric analysis, focuses on the frequencies and patterns of citations through time. It is an important method in which researchers can come to understand the chronological development of treatments and current research directions, as well as characteristics of articles with the most impact.[2]

Bibliometric analysis in several medical, surgical, and radiology specialties has previously been published.[3-10] Some of these have provided an overview of both the diagnostic and interventional radiology literature. The aim of this study was to analyze the 100 most cited articles in the endovascular treatment of BAVMs by examining their citation count, year of publication, authorship, institution, country of origin, journal of publication, topics of articles, article type, and level of evidence.

Methods

Identification of top-cited articles

A retrospective bibliometric analysis was performed between April and May 2020 to identify the articles of interest by using the "Web of Science(WoS)" platform (www.webofknowledge.com), which is an online scientific citation index database produced by the Institute for Scientific Information. Google Scholar (scholar.google.com) was used as a secondary index database to expand our literature source and act as a comparison to the Web of Science in terms of the number of citations. The search criteria include all articles published in English. The primary search keywords included "cerebral/brain/intracranial arteriovenous malformation," and "endovascular/treatment/intervention/emboliz(s)ation." The search was further expanded by introducing the name of embolization agents such as bucrylate, nonadhesive liquid, calcium alginate gel, copolymer, etc., and wildcards search to find plural or inflected forms of words. The results were subsequently filtered and ranked according to their number of citations.

Analysis of the most cited articles

Further analysis of the articles was manually performed by three reviewers (DL, YR, and JM) to obtain relevant information for citation analysis. The focus of the analysis included the total citation count, citation per year (obtained via Web of Science), year of publication, authorship, journal-title and impact factor (IF) (obtained via Thomson Reuters' Journal Citation Reports), article topics, article type (systematic reviews, randomized controlled trials, prospective studies (clinical, experimental, and animal), retrospective studies, case series, review articles, and case reports) and level of evidence (based on the Australian National Health and Medical Research Council [NHMRC] and Oxford Centre for Evidence-based Medicine [CEBM] guidelines).[11] The final results were reviewed and collated by the senior author (HA) separately from the initial review to minimize selection bias.

Results

Number of citations and citation trends

Table 1 shows the 100 most cited papers in the endovascular treatment of BAVMs ranked according to their total citation number based on the Web of Science between the years 1900 and 2020. The number of citations ranged from 56 to 471. Google Scholar provided a similar ranking trend but the number of citations of each individual article was generally higher than Web of Science. The mean total number of citations from Google Scholar was 174.05 (median = 140.0) compared to 106.51 from Web of Science (median = 85.5).

The most cited paper according to the Web of Science is "Medical management with or without interventional therapy for unruptured BAVMs (A Randomized Trial of Unruptured Brain Arteriovenous Malformations [ARUBA]): A multicenter, nonblinded, randomized trial" (n = 471) published in 2014 in The Lancet.[12] It also features the highest average citations per year (n = 67.29) and is the most cited article according to Google Scholar (n = 670). The oldest article in the list is "Artificial Embolization of Cerebral Arteries: Report of Use In A Case Of Arteriovenous Malformation" published by the Journal of the American Medical Association (JAMA) in 1960.[15] The article with the lowest number of citations in the top 100 list is "Combined endovascular embolization and stereotactic radiosurgery in the treatment of large arteriovenous malformations" (n = 56) published in the Journal of Neurosurgery in 2011.[111]

Publication years

Most of the top 100 papers were published between 1990 and 2009 (n = 76) with a minority (13%) being published in the last decade [Table 2]. Despite the low number of top 100 papers published before 1970 (n = 2), they ranked as the 4th and 24th most cited papers on the list. The most recently published article was "Embolization-Induced Angiogenesis In Cerebral Arteriovenous Malformations" published in the Journal of Clinical Neuroscience in

Table 1: Top 100 most cited articles in the field of endovascular treatment of brain arteriovenous malformations

Rank	Article	Wos citations	Average citation per year	Google scholar citations
1	Mohr JP, Parides MK, Stapf C, Moquete E, Moy CS, Overbey JR, *et al*. Medical management with or without interventional therapy for unruptured brain arteriovenous malformations (ARUBA): A multicentre, non-blinded, randomised trial. Lancet 2014;383:614-21.[12]	471	67.29	670
2	Ogilvy CS, Stieg PE, Awad I, Brown RD, Kondziolka D, Rosenwasser R, *et al*. Recommendations for the management of intracranial arteriovenous malformations - A statement for healthcare professionals from a special writing group of the stroke council, American Stroke Association. Stroke 2001;32:1458-71.[13]	275	13.75	367
3	Gobin YP, Laurent A, Merienne L, Schlienger M, Aymard A, Houdart E, *et al*. Treatment of brain arteriovenous malformations by embolization and radiosurgery. J Neurosurg 1996;85:19-28.[14]	266	10.64	444
4	Luessenhop AJ, Spence WT. Artificial embolization of cerebral arteries. Report of use in a case of arteriovenous malformation. J Am Med Assoc 1960;172:1153-5.[15]	248	4.07	457
5	van Beijnum J, van der Worp HB, Buis DR, Al-Shahi Salman R, Kappelle LJ, Rinkel GJ, *et al*. Treatment of brain arteriovenous malformations: A systematic review and meta-analysis. JAMA 2011;306:2011-9.[16]	235	23.5	353
6	Jahan R, Murayama Y, Gobin YP, Duckwiler GR, Vinters HV, Viñuela F. Embolization of arteriovenous malformations with Onyx: Clinicopathological experience in 23 patients. Neurosurgery 2001;48:984-95.[17]	204	10.2	401
7	Viñuela F, Dion JE, Duckwiler G, Martin NA, Lylyk P, Fox A, *et al*. Combined endovascular embolization and surgery in the management of cerebral arteriovenous malformations: Experience with 101 cases. J Neurosurg 1991;75:856-64.[18]	186	6.2	321
8	Debrun G, Vinuela F, Fox A, Drake CG. Embolization of cerebral arteriovenous-malformations with bucrylate - experience in 46 cases. J Neurosurg 1982;56:615-27.[19]	181	4.64	274
9	van Rooij WJ, Sluzewski M, Beute GN. Brain AVM embolization with Onyx. AJNR Am J Neuroradiol 2007;28:172-7.[20]	176	12.57	314
10	Saatci I, Geyik S, Yavuz K, Cekirge HS. Endovascular treatment of brain arteriovenous malformations with prolonged intranidal Onyx injection technique: Long-term results in 350 consecutive patients with completed endovascular treatment course. J Neurosurg 2011;115:78-88.[21]	168	16.8	258
11	Jafar JJ, Davis AJ, Berenstein A, Choi IS, Kupersmith MJ. The effect of embolization with N-butyl cyanoacrylate prior to surgical resection of cerebral arteriovenous malformations. J Neurosurg 1993;78:60-9.[22]	168	6	283
12	Fournier D, TerBrugge KG, Willinsky R, Lasjaunias P, Montanera W. Endovascular treatment of intracerebral arteriovenous malformations: Experience in 49 cases. J Neurosurg 1991;75:228-33.[23]	166	5.53	248
13	Weber W, Kis B, Siekmann R, Kuehne D. Endovascular treatment of intracranial arteriovenous malformations with onyx: Technical aspects. AJNR Am J Neuroradiol 2007;28:371-7.[24]	165	11.79	308
14	Barrow DL, Boyer KL, Joseph GJ. Intraoperative angiography in the management of neurovascular disorders. Neurosurgery 1992;30:153-9.[25]	163	5.62	235
15	Murayama Y, Viñuela F, Ulhoa A, Akiba Y, Duckwiler GR, Gobin YP, *et al*. Nonadhesive liquid embolic agent for cerebral arteriovenous malformations: Preliminary histopathological studies in swine rete mirabile. Neurosurgery 1998;43:1164-75.[26]	161	7	248
16	Qureshi AI, Luft AR, Sharma M, Guterman LR, Hopkins LN. Prevention and treatment of thromboembolic and ischemic complications associated with endovascular procedures: Part II—Clinical aspects and recommendations. Neurosurgery 2000;46:1360-75.[27]	158	7.52	273
17	Debrun GM, Aletich V, Ausman JI, Charbel F, Dujovny M. Embolization of the nidus of brain arteriovenous malformations with n-butyl cyanoacrylate. Neurosurgery 1997;40:112-20.[28]	154	6.42	255
18	Mounayer C, Hammami N, Piotin M, Spelle L, Benndorf G, Kessler I, *et al*. Nidal embolization of brain arteriovenous malformations using Onyx in 94 patients. AJNR Am J Neuroradiol 2007;28:518-23.[29]	151	10.79	257
19	Andrade-Souza YM, Ramani M, Scora D, Tsao MN, terBrugge K, Schwartz ML. Embolization before radiosurgery reduces the obliteration rate of arteriovenous malformations. Neurosurgery 2007;60:443-51.[30]	150	10.71	222

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Rank	Article	Wos citations	Average citation per year	Google scholar citations
20	Choi JH, Mohr JP. Brain arteriovenous malformations in adults. Lancet Neurol 2005;4:299-308.[31]	141	8.81	252
21	Meisel HJ, Mansmann U, Alvarez H, Rodesch G, Brock M, Lasjaunias P. Cerebral arteriovenous malformations and associated aneurysms: Analysis of 305 cases from a series of 662 patients. Neurosurgery 2000;46:793-800.[32]	141	6.71	232
22	Katsaridis V, Papagiannaki C, Aimar E. Curative embolization of cerebral arteriovenous malformations (AVMs) with Onyx in 101 patients. Neuroradiology 2008;50:589-97.[33]	137	10.54	259
23	Luessenhop AJ, Kachmann R, Shevlin W, Ferrero AA. Clinical evaluation of artificial embolization in management of large cerebral arteriovenous malformations. J Neurosurg 1965;23:400.[34]	134	2.39	154
24	Panagiotopoulos V, Gizewski E, Asgari S, Regel J, Forsting M, Wanke I. Embolization of intracranial arteriovenous malformations with ethylene-vinyl alcohol copolymer (Onyx). AJNR Am J Neuroradiol 2009;30:99-106.[35]	130	10.83	231
25	Pollak JS, White RI Jr. The use of cyanoacrylate adhesives in peripheral embolization. J Vasc Interv Radiol 2001;12:907-13.[36]	127	6.35	219
26	Frizzel RT, Fisher WS 3rd. Cure, morbidity, and mortality associated with embolization of brain arteriovenous malformations: A review of 1246 patients in 32 series over a 35-year period. Neurosurgery 1995;37:1031-9.[37]	126	4.85	207
27	Becker TA, Kipke DR, Brandon T. Calcium alginate gel: A biocompatible and mechanically stable polymer for endovascular embolization. J Biomed Mater Res 2001;54:76-86.[38]	125	6.25	218
28	Gandhi D, Chen J, Pearl M, Huang J, Gemmete JJ, Kathuria S. Intracranial dural arteriovenous fistulas: Classification, imaging findings, and treatment. AJNR Am J Neuroradiol 2012;33:1007-13.[39]	118	13.11	218
29	Hartmann A, Pile-Spellman J, Stapf C, Sciacca RR, Faulstich A, Mohr JP, *et al*. Risk of endovascular treatment of brain arteriovenous malformations. Stroke 2002;33:1816-20.[40]	117	6.16	209
30	ApSimon HT, Reef H, Phadke RV, Popovic EA. A population-based study of brain arteriovenous malformation: Long-term treatment outcomes. Stroke 2002;33:2794-800.[41]	110	5.79	214
31	Purdy P, Horowitz M, Kopitnik T, Samson D, Dion J, Joseph G, *et al*. N-butyl cyanoacrylate embolization of cerebral arteriovenous malformations: Results of a prospective, randomized, multi-center trial. AJNR Am J Neuroradiol 2002;23:748-55.[42]	110	5.79	133
32	Taylor CL, Dutton K, Rappard G, Pride GL, Replogle R, Purdy PD, *et al*. Complications of preoperative embolization of cerebral arteriovenous malformations. J Neurosurg 2004;100:810-2.[43]	103	6.06	179
33	Hoh BL, Chapman PH, Loeffler JS, Carter BS, Ogilvy CS. Results of multimodality treatment for 141 patients with brain arteriovenous malformations and seizures: Factors associated with seizure incidence and seizure outcomes. Neurosurgery 2002;51:303-9.[44]	103	5.42	180
34	Lasjaunias P, Hui F, Zerah M, Garcia-Monaco R, Malherbe V, Rodesch G, *et al*. Cerebral arteriovenous malformations in children. Management of 179 consecutive cases and review of the literature. Childs Nerv Syst 1995;11:66-79.[45]	102	3.92	138
35	Kim LJ, Albuquerque FC, Spetzler RF, McDougall CG. Postembolization neurological deficits in cerebral arteriovenous malformations: Stratification by arteriovenous malformation grade. Neurosurgery 2006;59:53-9.[46]	101	6.73	86
36	Chang SD, Marcellus ML, Marks MP, Levy RP, Do HM, Steinberg GK. Multimodality treatment of giant intracranial arteriovenous malformations. Neurosurgery 2003;53:1-1.[47]	99	5.5	209
37	Celli P, Ferrante L, Palma L, Cavedon G. Cerebral arteriovenous malformations in children. Clinical features and outcome of treatment in children and in adults. Surg Neurol 1984;22:43-9.[48]	99	2.68	160
38	Salman RA, White PM, Counsell CE, du Plessis J, van Beijnum J, Josephson CB, *et al*. Outcome after conservative management or intervention for unruptured brain arteriovenous malformations. J Am Med Assoc 2014;311:1661-9.[49]	97	13.86	144
39	Natarajan SK, Ghodke B, Britz GW, Born DE, Sekhar LN. Multimodality treatment of brain arteriovenous malformations with microsurgery after embolization with onyx: Single-center experience and technical nuances. Neurosurgery 2008;62:1213-25.[50]	95	7.31	164

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Rank	Article	Wos citations	Average citation per year	Google scholar citations
40	Meyers PM, Schumacher HC, Higashida RT, Barnwell SL, Creager MA, Gupta R, *et al*. Indications for the performance of intracranial endovascular neurointerventional procedures. A scientific statement from the American Heart Association Council on Cardiovascular Radiology and Intervention, Stroke Council, Council on Cardiovascular Surgery and Anesthesia, Interdisciplinary Council on Peripheral Vascular Disease, and Interdisciplinary Council on Quality of Care and Outcomes Research. J Neurointerv Surg 2010;2:177-88.[51]	94	8.55	177
41	Beaujeux R, Laurent A, Wassef M, Casasco A, Gobin YP, Aymard A, *et al*. Trisacryl gelatin microspheres for therapeutic embolization. 2. Preliminary clinical evaluation in tumors and arteriovenous malformations. Am J Neuroradiol 1996;17:541-8.[52]	94	3.76	190
42	Ledezma CJ, Hoh BL, Carter BS, Pryor JC, Putman CM, Ogilvy CS. Complications of cerebral arteriovenous malformation embolization: Multivariate analysis of predictive factors. Neurosurgery 2006;58:602-11.[53]	93	6.2	163
43	Loh Y, Duckwiler GR, Onyx Trial Investigators. A prospective, multicenter, randomized trial of the Onyx liquid embolic system and N-butyl cyanoacrylate embolization of cerebral arteriovenous malformations. Clinical article. J Neurosurg 2010;113:733-41.[54]	92	8.36	146
44	Qureshi AI. Endovascular treatment of cerebrovascular diseases and intracranial neoplasms. Lancet 2004;363:804-13.[55]	92	5.41	198
45	Weber W, Kis B, Siekmann R, Jans P, Laumer R, Kühne D. Preoperative embolization of intracranial arteriovenous malformations with Onyx. Neurosurgery 2007;61:244-52.[56]	90	6.43	166
46	Söderman M, Andersson T, Karlsson B, Wallace MC, Edner G. Management of patients with brain arteriovenous malformations. Eur J Radiol 2003;46:195-205.[57]	90	5	188
47	Vinters HV, Lundie MJ, Kaufmann JC. Long-term pathological follow-up of cerebral arteriovenous malformations treated by embolization with bucrylate. N Engl J Med 1986;314:477-83.[58]	90	2.57	123
48	Germano IM, Davis RL, Wilson CB, Hieshima GB. Histopathological follow-up study of 66 cerebral arteriovenous malformations after therapeutic embolization with polyvinyl alcohol. J Neurosurg 1992;76:607-14.[59]	89	3.07	111
49	Wikholm G, Lundqvist C, Svendsen P. Embolization of cerebral arteriovenous malformations: Part I—Technique, morphology, and complications. Neurosurgery 1996;39:448-57.[60]	87	3.48	193
50	Garcia-Monaco R, De Victor D, Mann C, Hannedouche A, Terbrugge K, Lasjaunias P. Congestive cardiac manifestations from cerebrocranial arteriovenous shunts. Endovascular management in 30 children. Childs Nerv Syst 1991;7:48-52.[61]	86	2.87	125
51	Stapf C, Mohr JP, Choi JH, Hartmann A, Mast H. Invasive treatment of unruptured brain arteriovenous malformations is experimental therapy. Curr Opin Neurol 2006;19:63-8.[62]	85	5.67	131
52	Kish JW, Katz MD, Marx MV, Harrell DS, Hanks SE. N-butyl cyanoacrylate embolization for control of acute arterial hemorrhage. J Vasc Interv Radiol 2004;15:689-95.[63]	85	5	148
53	Chaloupka JC, Huddle DC, Alderman J, Fink S, Hammond R, Vinters HV. A reexamination of the angiotoxicity of superselective injection of DMSO in the swine rete embolization model. AJNR Am J Neuroradiol 1999;20:401-10.[64]	85	3.86	145
54	Mathis JA, Barr JD, Horton JA, Jungreis CA, Lunsford LD, Kondziolka DS, *et al*. The efficacy of particulate embolization combined with stereotactic radiosurgery for treatment of large arteriovenous malformations of the brain. AJNR Am J Neuroradiol 1995;16:299-306.[65]	85	3.27	154
55	Haw CS, terBrugge K, Willinsky R, Tomlinson G. Complications of embolization of arteriovenous malformations of the brain. J Neurosurg 2006;104:226-32.[66]	84	5.6	143
56	Purdy PD, Samson D, Batjer HH, Risser RC. Preoperative embolization of cerebral arteriovenous malformations with polyvinyl alcohol particles: Experience in 51 adults. AJNR Am J Neuroradiol 1990;11:501-10.[67]	84	2.71	126
57	Lee BH, West B, McLemore R, Pauken C, Vernon BL. In-situ injectable physically and chemically gelling NIPAAm-based copolymer system for embolization. Biomacromolecules 2006;7:2059-64.[68]	83	5.53	110
58	Pasqualin A, Scienza R, Cioffi F, Barone G, Benati A, Beltramello A, *et al*. Treatment of cerebral arteriovenous malformations with a combination of preoperative embolization and surgery. Neurosurgery 1991;29:358-68.[69]	82	2.73	128

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59	Deruty R, Pelissou-Guyotat I, Mottolese C, Bascoulergue Y, Amat D. The combined management of cerebral arteriovenous malformations. Experience with 100 cases and review of the literature. Acta Neurochir (Wien) 1993;123:101-12.[70]	79	2.82	124
60	Luessenhop AJ, Presper JH. Surgical embolization of cerebral arteriovenous malformations through internal carotid and vertebral arteries. Long-term results. J Neurosurg 1975;42:443-51.[71]	79	1.72	127
61	Yu SC, Chan MS, Lam JM, Tam PH, Poon WS. Complete obliteration of intracranial arteriovenous malformation with endovascular cyanoacrylate embolization: Initial success and rate of permanent cure. AJNR Am J Neuroradiol 2004;25:1139-43.[72]	78	4.59	137
62	Collice M, D'Aliberti G, Arena O, Solaini C, Fontana RA, Talamonti G. Surgical treatment of intracranial dural arteriovenous fistulae: Role of venous drainage. Neurosurgery 2000;47:56-66.[73]	76	3.62	133
63	Geibprasert S, Pongpech S, Jiarakongmun P, Shroff MM, Armstrong DC, Krings T. Radiologic assessment of brain arteriovenous malformations: What clinicians need to know. Radiographics 2010;30:483-501.[74]	74	6.73	140
64	Humphreys RP, Hoffman HJ, Drake JM, Rutka JT. Choices in the 1990s for the management of pediatric cerebral arteriovenous malformations. Pediatr Neurosurg 1996;25:277-85.[75]	74	2.96	126
65	DeMeritt JS, Pile-Spellman J, Mast H, Moohan N, Lu DC, Young WL, *et al*. Outcome analysis of preoperative embolization with N-butyl cyanoacrylate in cerebral arteriovenous malformations. AJNR Am J Neuroradiol 1995;16:1801-7.[76]	74	2.85	135
66	Bank WO, Kerber CW, Cromwell LD. Treatment of intra-cerebral arteriovenous-malformations with isobutyl 2-cyanoacrylate - initial clinical-experience. Radiology 1981;139:609-16.[77]	74	1.85	92
67	Weon YC, Yoshida Y, Sachet M, Mahadevan J, Alvarez H, Rodesch G, *et al*. Supratentorial cerebral arteriovenous fistulas (AVFs) in children: Review of 41 cases with 63 non choroidal single-hole AVFs. Acta Neurochir (Wien) 2005;147:17-31.[78]	73	4.56	111
68	Di Rocco C, Tamburrini G, Rollo M. Cerebral arteriovenous malformations in children. Acta Neurochir (Wien) 2000;142:145-56.[79]	73	3.48	138
69	Yakes WF, Krauth L, Ecklund J, Swengle R, Dreisbach JN, Seibert CE, *et al*. Ethanol endovascular management of brain arteriovenous malformations: Initial results. Neurosurgery 1997;40:1145-52.[80]	73	3.04	140
70	Wedderburn CJ, van Beijnum J, Bhattacharya JJ, Counsell CE, Papanastassiou V, Ritchie V, *et al*. Outcome after interventional or conservative management of unruptured brain arteriovenous malformations: A prospective, population-based cohort study. Lancet Neurol 2008;7:223-30.[81]	72	5.54	116
71	Kusske JA, Kelly WA. Embolization and reduction of the "steal" syndrome in cerebral arteriovenous malformations. J Neurosurg 1974;40:313-21.[82]	72	1.53	102
72	Hartmann A, Mast H, Mohr JP, Pile-Spellman J, Connolly ES, Sciacca RR, *et al*. Determinants of staged endovascular and surgical treatment outcome of brain arteriovenous malformations. Stroke 2005;36:2431-5.[83]	70	4.38	123
73	Buell TJ, Ding D, Starke RM, Webster Crowley R, Liu KC. Embolization-induced angiogenesis in cerebral arteriovenous malformations. J Clin Neurosci 2014;21:1866-71.[84]	69	9.86	85
74	Li X, Liu W, Ye G, Zhang B, Zhu D, Yao K, *et al*. Thermosensitive N-isopropylacrylamide-N-propylacrylamide-vinyl pyrrolidone terpolymers: Synthesis, characterization and preliminary application as embolic agents. Biomaterials 2005;26:7002-11.[85]	69	4.31	78
75	Meisel HJ, Mansmann U, Alvarez H, Rodesch G, Brock M, Lasjaunias P. Effect of partial targeted N-butyl-cyano-acrylate embolization in brain AVM. Acta Neurochir (Wien) 2002;144:879-87.[86]	69	3.63	119
76	Hillman J. Population-based analysis of arteriovenous malformation treatment. J Neurosurg 2001;95:633-7.[87]	68	3.4	124
77	Mottu F, Rüfenacht DA, Laurent A, Doelker E. Iodine-containing cellulose mixed esters as radiopaque polymers for direct embolization of cerebral aneurysms and arteriovenous malformations. Biomaterials 2002;23:121-31.[88]	67	3.53	86
78	Miyamoto S, Hashimoto N, Nagata I, Nozaki K, Morimoto M, Taki W, *et al*. Posttreatment sequelae of palliatively treated cerebral arteriovenous malformations. Neurosurgery 2000;46:589-94.[89]	67	3.19	121

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79	Marks MP, Lane B, Steinberg GK, Snipes GJ. Intranidal aneurysms in cerebral arteriovenous malformations: Evaluation and endovascular treatment. Radiology 1992;183:355-60.[90]	67	2.31	140
80	Purdy PD, Batjer HH, Samson D. Management of hemorrhagic complications from preoperative embolization of arteriovenous malformations. J Neurosurg 1991;74:205-11.[91]	67	2.23	102
81	Jungreis CA, Horton JA, Hecht ST. Blood pressure changes in feeders to cerebral arteriovenous malformations during therapeutic embolization. AJNR Am J Neuroradiol 1989;10:575-7.[92]	67	2.09	71
82	Maimon S, Strauss I, Frolov V, Margalit N, Ram Z. Brain arteriovenous malformation treatment using a combination of Onyx and a new detachable tip microcatheter, SONIC: Short-term results. AJNR Am J Neuroradiol 2010;31:947-54.[93]	66	6	108
83	Ayad M, Eskioglu E, Mericle RA. Onyx®: A unique neuroembolic agent. Expert Rev Med Devices 2006;3:705-15.[94]	65	4.33	101
84	Wikholm G. Occlusion of cerebral arteriovenous malformations with N-butyl cyano-acrylate is permanent. AJNR Am J Neuroradiol 1995;16:479-82.[95]	65	2.5	93
85	Hurst RW, Berenstein A, Kupersmith MJ, Madrid M, Flamm ES. Deep central arteriovenous malformations of the brain: The role of endovascular treatment. J Neurosurg 1995;82:190-5.[96]	65	2.5	104
86	Hladky JP, Lejeune JP, Blond S, Pruvo JP, Dhellemmes P. Cerebral arteriovenous malformations in children: Report on 62 cases. Childs Nerv Syst 1994;10:328-33.[97]	65	2.41	95
87	Paulsen RD, Steinberg GK, Norbash AM, Marcellus ML, Marks MP. Embolization of basal ganglia and thalamic arteriovenous malformations. Neurosurgery 1999;44:991-6.[98]	64	2.91	94
88	Young WL, Pile-Spellman J. Anesthetic considerations for interventional neuroradiology. Anesthesiology 1994;80:427-56.[99]	64	2.37	164
89	Wallace RC, Flom RA, Khayata MH, Dean BL, McKenzie J, Rand JC, *et al*. The safety and effectiveness of brain arteriovenous malformation embolization using acrylic and particles: The experiences of a single institution. Neurosurgery 1995;37:606-15.[100]	62	2.38	84
90	Cromwell LD, Harris AB. Treatment of cerebral arteriovenous malformations: A combined neurosurgical and neuroradiological approach. J Neurosurg 1980;52:705-8.[101]	62	1.51	92
91	Boulos R, Kricheff II, Chase NE. Value of cerebral angiography in the embolization treatment of cerebral arteriovenous malformations. Radiology 1970;97:65-70.[102]	62	1.22	66
92	Cahill AM, Nijs EL. Pediatric vascular malformations: Pathophysiology, diagnosis, and the role of interventional radiology. Cardiovasc Intervent Radiol 2011;34:691-704.[103]	61	6.1	105
93	Henkes H, Nahser HC, Berg-Dammer E, Weber W, Lange S, Kühne D. Endovascular therapy of brain AVMs prior to radiosurgery. Neurol Res 1998;20:479-92.[104]	61	2.65	107
94	Halbach VV, Higashida RT, Dowd CF, Barnwell SL, Hieshima GB. Management of vascular perforations that occur during neurointerventional procedures. AJNR Am J Neuroradiol 1991;12:319-27.[105]	60	2	109
95	Fournier D, Terbrugge K, Rodesch G, Lasjaunias P. Revascularization of brain arteriovenous malformations after embolization with bucrylate. Neuroradiology 1990;32:497-501.[106]	60	1.94	83
96	Rutledge WC, Abla AA, Nelson J, Halbach VV, Kim H, Lawton MT. Treatment and outcomes of ARUBA-eligible patients with unruptured brain arteriovenous malformations at a single institution. Neurosurg Focus 2014;37:E8.[107]	60	10	82
97	Sure U, Butz N, Siegel AM, Mennel HD, Bien S, Bertalanffy H. Treatment-induced neoangiogenesis in cerebral arteriovenous malformations. Clin Neurol Neurosurg 2001;103:29-32.[108]	57	2.85	99
98	Sorimachi T, Koike T, Takeuchi S, Minakawa T, Abe H, Nishimaki K, *et al*. Embolization of cerebral arteriovenous malformations achieved with polyvinyl alcohol particles: Angiographic reappearance and complications. AJNR Am J Neuroradiol 1999;20:1323-8.[109]	57	2.59	102
99	Guo WY, Wikholm G, Karlsson B, Lindquist C, Svendsen P, Ericson K. Combined embolization and gamma knife radiosurgery for cerebral arteriovenous malformations. Acta Radiol 1993;34:600-6.[110]	57	2.04	74
100	Blackburn SL, Ashley WW Jr., Rich KM, Simpson JR, Drzymala RE, Ray WZ, *et al*. Combined endovascular embolization and stereotactic radiosurgery in the treatment of large arteriovenous malformations. J Neurosurg 2011;114:1758-67.[111]	56	5.6	90

November 2014 with a total citation count of 69 on Web of Science and 85 on Google Scholar.[84]

Authorship

There is a relatively even spread of authors who have contributed to the top 100 most cited papers in the field. Twenty-six authors contributed three or more articles on the list. Eleven of these authors contributed four or more articles [Table 3]. Pierre Lasjaunias is the most published author contributing a total of seven articles on the list. Alfred J. Luessenhop has the most published articles as first author (n = 3).

Journals

Thirty journals contributed to the top 100 with 13 journals publishing 2 or more articles on the list [Table 4]. IF for each journal was obtained based on Journal Citation Reports 2018, except for Surgical Neurology, which was based on the latest available data in 2011. Neurosurgery provided the highest number of articles in the list with 21 articles followed by the Journal of Neurosurgery and the American Journal of Neuroradiology providing 18 and 17 articles, respectively. These three Journals contributed 15 of the top 20 most cited articles and 56% of the articles in the entire list.

The journals with the highest IF include the New England Journal of Medicine (IF 70.67), Lancet (IF 59.102), JAMA (IF 51.273), and Lancet Neurology (IF 28.755). JAMA contributed 3 articles to the list, and 2 of the 3 articles ranked in the top 5 most cited articles. Lancet Neurology and Lancet each contributed 2 articles to the top 100 list, including the most cited article in the field of endovascular BAVM treatment which was the ARUBA multicenter study by Mohr *et al*. in 2014 whilst New England Journal of Medicine contributed one article to the top 100 list.[12]

Table 2: Top 100 most cited articles in the field of endovascular treatment of brain arteriovenous malformations published in each decade

Decades	Number of articles
1960-1969	2
1970-1979	3
1980-1989	6
1990-1999	34
2000-2009	42
2010-2019	13

Country and institute of origin

The top 100 most cited articles were produced by authors from 21 different countries. Fifty-two percent of the articles were contributed by the United States of America followed by 16 articles from France and 12 articles from

Table 3: Authors contributed three or more articles to the top 100 most cited articles in the endovascular treatment of brain arteriovenous malformations

Name	Number of articles	Position on author list
Lasjaunias, P	7	First (1), Fourth (2), Sixth (3), Seventh (1)
Mohr, JP	5	First (1), Second (1), Third (1), Sixth (1), Eighth (1)
Terbrugge, K	5	Second (3), Fifth (1), Sixth (1)
Rodesch, G	5	Third (1), Fourth (2), Sixth (2)
Alvarez, H	4	Third (2), Fifth (1), Eighth (1)
Gobin, YP	4	First (1), Third (1), Fifth (1), Sixth (1)
Hartmann, A	4	First (2), Fourth (1), Twelfth (1)
Mast, H	4	Second (1), Third (1), Fifth (1), Eighth (1)
Salman, RAS	4	First (1), Fourth (1), Seventh (1), Tenth (1)
Stapf, C	4	First (1), Third (2), Eighth (1)
Vinters, HV	4	First (1), Fifth (1), Sixth (1), Seventh (1)
Vinuela, F	4	First (1), Second (2), Sixth (1)
Young, WL	4	First (1), Sixth (1), Seventh (1), Ninth (1)
Berenstein, A	3	Second (1), Third (1), Forty-second (1)
Duckwiler, GR	3	Second (1), Fourth (1), Fifth (1)
Halbach, VV	3	First (1), Fourth (1), Twenty-sixth (1)
Laurent, A	3	Second (2), Third (1)
Luessenhop, AJ	3	First (3)
Marks, MP	3	First (1), Third (1), Fifth (1)
Ogilvy, CS	3	First (1), Fifth (1), Sixth (1)
Purdy, PD	3	First (2), Sixth (1)
Samson, D	3	Second (1), Fourth (1), Tenth (1)
Steinberg, GK	3	Second (1), Third (1), Sixth (1)
Van Beijnum, J	3	First (1), Second (1), Fifth (1)
Weber, W	3	First (2), Fourth (1)
Wikholm, G	3	First (2), Second (1)

Table 4: Journals contributed to the top 100 articles with the corresponding number of articles published and impact factor

Journal	Number of papers published	Impact factor
Neurosurgery	21	4.605
Journal of Neurosurgery	18	4.13
American Journal of Neuroradiology	17	3.256
Acta Neurochirurgica	4	1.834
Stroke	4	6.058
Childs Nervous System	3	1.327
Jama-Journal of the American Medical Association	3	51.273
Radiology	3	7.608
Biomaterials	2	10.273
Journal of Vascular and Interventional Radiology	2	2.828
Lancet	2	59.102
Lancet Neurology	2	28.755
Neuroradiology	2	2.504
Acta Radiologica	1	1.586
Anesthesiology	1	6.424
Biomacromolecules	1	5.667
Cardiovascular and Interventional Radiology	1	1.928
Clinical Neurology and Neurosurgery	1	1.672
Current Opinion in Neurology	1	4.647
European Journal of Radiology	1	2.948
Expert Review of Medical Devices	1	2.212
Journal of Biomedical Materials Research	1	3.221
Journal of Clinical Neuroscience	1	1.593
Journal of Neurointerventional Surgery	1	3.925
Neurological Research	1	1.983
Neurosurgical Focus	1	2.891
New England Journal of Medicine	1	70.67
Pediatric Neurosurgery	1	0.783
Radiographics	1	3.923
Surgical Neurology	1	1.669

both Germany and Canada. University of California, Los Angeles contributed the most articles (n = 7), followed by Columbia University (n = 6) to the top 100 list. Twenty-five institutions published two or more articles in the top 100. Four articles did not contain institution data to be analyzed.

Topical distribution

Table 5 provides a summary of the topics covered by the top 100 most cited articles. Articles were categorized into five groups which include: Embolization agents (n = 33), complications and prognosis (n = 18), combined therapy (surgery, endovascular therapies, and radiosurgery) (n = 31), pathophysiology (n = 12) and novel endovascular techniques (n = 6). In terms of the patient age groups, 92 articles focused on the adult population and only 8 articles were related to the pediatric population.

Level of evidence and type of clinical study

The level of evidence and type of clinical studies for the top 100 articles are summarized in Table 6. Most of the articles were retrospective clinical studies (n = 33) or review articles (n = 20) corresponding to level IV/4 and V/5 (NHMRC/CEBM) evidence, respectively. There were three-level II/1b (NHMRC/CEBM) randomized clinical trials in the top 100 list, ranked 1st, 31^{st,} and 43rd, respectively. There were three systematic reviews, ranked 2nd, 5^{th,} and 40th in the top 100 articles, representing the highest level of evidence in the list. In addition, there were 21 prospective studies consisting of 17 clinical, 1 experimental, and 3 animal studies.

Discussion

Endovascular treatments for intracranial vascular pathology have rapidly progressed over the past few decades. This comprehensive citation analysis reflects the progression of endovascular treatment techniques, by itself or in combination with other treatment modalities, in the role of treating BAVMs. This trend is reflected by the increasing number of total citations of articles per year in Figure 1.

Overall, the top 100 articles relating to endovascular treatment of BAVMs have fewer total citation counts

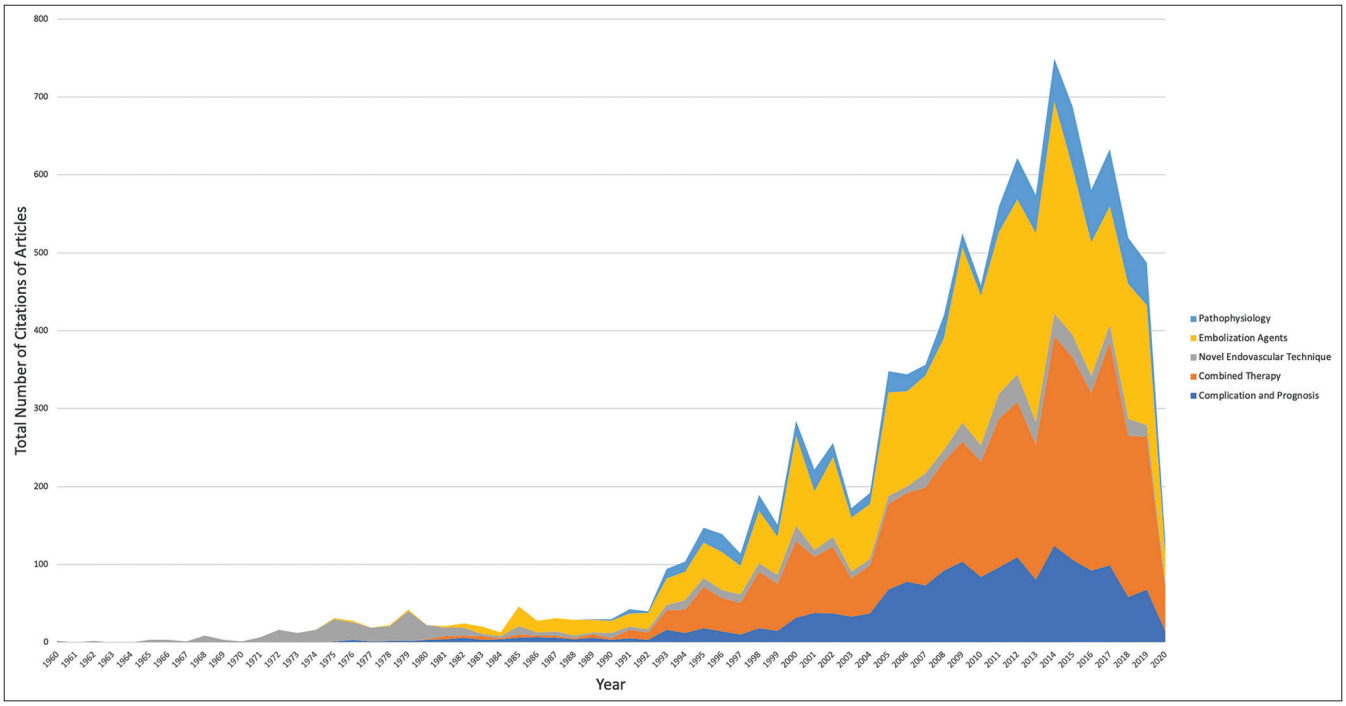

Figure 1: Total number of citations for the top 100 articles each year, classified by categories of topics

Table 5: Main topics covered within the top 100 articles and number of articles from each topic

Subject	Number of articles
Combined therapy	31
Embolization agents	33
Pathophysiology	12
Novel endovascular technique	6
Complication and prognosis	18

Table 6: Levels of evidence and article types in the top 100 articles list

Level of Evidence		Article Type	No. of Articles
NHMRC	CEBM		
I	1	Systematic review	3
II	1b	Randomized controlled trial	3
III	3	Original Prospective	
		- Clinical	17
		- Experimental	1
		- Animal	3
IV	4	Original Retrospective	
		- Clinical	33
		Case series	17
V	5	Review	20
		Case report	3

compared to other specialties.[3-10] Citation analysis shows that the total number of citations on the list ranged from 56 to 471 based on the Web of Science bibliometric with an average 106.51 and a median of 85.5. In contrast, within the field of diabetic research, by 2016, the top citation number was 10,292 with a mean of 2,129.[10] Furthermore, the total number of citations for endovascular treatment of BAVMs is substantially lower than average within the subspecialties of interventional radiology. By 2015, the top-cited article in interventional radiology had a citation count of 2,497, with a mean of 320 in the top 100.[3] This disparity is partially due to BAVM being a relatively less common disease than other conditions such as cerebral aneurysm and acute ischemic stroke. In addition, it reflects that the endovascular treatment of BAVMs is a relatively new and specialized area within interventional neuroradiology. Similar focused bibliometric analyses have demonstrated low citation counts in other subspecialties, such as the citation analysis of total hip arthroplasty, as a subspecialty of orthopedic surgery and the analysis of hand surgery as a subspecialty of plastic surgery.[4,9]

Table 2 indicates that most of the top 100 articles regarding the endovascular treatment of BAVMs were published after 1990 ($n = 89$) with the peak decade being the 2000s ($n = 42$). It is likely driven by refinements in angiographic techniques and endovascular equipment and it also demonstrates the contemporary nature of the endovascular treatment of BAVMs. In contrast, most of the top 100 articles from more established specialties such as plastic surgery and orthopedic surgery were published in the 1980s.[4,6] The case report "Artificial Embolization of Cerebral Arteries Report of Use in a Case of Arteriovenous Malformation" published in 1960 represented the earliest reported case of a BAVM treated by embolization, introducing four methyl-methacrylate emboli via the left common carotid artery.[15] Again,

in contrast to other more established fields such as orthopedic surgery, the first published article in this field could be tracked back to the 19th century.[6]

Our analysis reveals a relatively narrow contribution of authors in the field of endovascular BAVM treatment. Four authors contributed five or more articles. Three journals, namely, Neurosurgery, the Journal of Neurosurgery, and the American Journal of Neuroradiology, contributed 56 articles in the top 100 list. In contrast, only 6 articles were published in journals with IF >50. This reflects a predilection for authors in the field to publish their work in specialized journals. The remaining articles were spread evenly among 27 journals across different specialties including pediatrics, neurology, ophthalmology, radiology, bioengineering and biochemistry, highlighting the multidisciplinary approach to BAVM treatment.

The most common topic in the top 100 articles related to embolization agents. The choice of embolization agents was of particular interest to neuro-endovascular specialists. Historically, autologous blood clot, fascial strips, muscles, and silk have all been used.[112] The use of methyl-methacrylate in the 1960 case report had a profound impact on the treatment of BAVMs.[15] Other embolic materials started to come to fore in the 1980s including bucrylate (n-butyl-2 cyanoacrylate).[19] The interest in evaluating different embolic agents started in the early 1990s with exponential growth of total citations of articles per year in this area. Figure 1 suggests that such a growth of interest was the major contributor to the increasing number of articles published after 1990. Of note, three articles on the list were pure biochemical experimental papers relating to the development of new embolic agents for BAVM treatment, all published around 2000, which included nonadhesive liquid, calcium alginate gel, and copolymer.[26,38,68]

The second most common topic in the endovascular treatment of BAVMs was the evaluation of the effectiveness of endovascular treatment compared to conservative, surgical, or radiosurgical treatment, either alone or as a combined therapy. This topic also included 5 out of 8 articles in the top 100 list that addressed the pediatric population, suggesting the focus of endovascular treatment of BAVMs in children was on the embolization outcomes compared to other methods rather than analysis of embolization agents. There were three systematic reviews in the top 100 list and all evaluated the impact of combined therapy. This topic also included the highly controversial ARUBA study. ARUBA represented an important turning point in the history of BAVM management but has been criticized since its publication in 2014.[12] ARUBA suggested an unexpected conclusion that conservative management alone, was superior to conservative management with interventions in the prevention of death or stroke in patients with BAVMs, which challenged the prevailing dogma supporting intervention.[12] Due to its controversy, it was not only the most cited article in the top 100 list (n = 471) but also had the highest average citations per year (n = 67.29). One of the strengths of ARUBA was that up until 2020, it has remained the only multicenter, multinational randomized trial on unruptured BAVMs that compares medical treatment alone and medical treatment with intervention, with 223 patients recruited over 39 clinical sites in 9 countries.[12] Other strengths of ARUBA included high data quality with 98% data completeness, strong patient adherence, and unbiased primary outcome measurements, stroke or death.[12] On the other hand, a recent systematic review questioned ARUBA's flaws in the primary hypothesis of putting intervention groups as the control and testing conservative treatment as experimental group.[113] It further questioned ARUBA's choice of analysis methods by grouping all interventional methods into one arm but not individually to validate individual risks and benefits.[113] Many other critiques also focused on the low enrolment of 223 patients, short follow-up period (mean of 33.3 months), suspected recruitment bias, and choice of outcome measures in favor of conservative management.[113] On reflection of ARUBA, it stimulated many thoughtful discussions among experts in the field and encouraged further research in the field of BAVMs. A further randomized trial Treatment of Brain AVMs (TOBAS) is currently in the recruitment phase, with similar inclusion and exclusion criteria to ARUBA and its results are eagerly awaited.[114] As there are still no formal guidelines on the treatment of unruptured BAVMs, future randomized trials are needed to provide guidance and evidence to support the different management methods of BAVMs in the presence of uncertainty.

The citation analysis published by Kim *et al*. in 2017 assessing the top 100 articles in neuro-interventional research shared some similarities with our results, especially with regard to the pattern of article distributions among authors and countries of origin.[5] However, they demonstrated that the majority of top-cited papers in neuro-interventional research were related to "endovascular treatment of cerebral aneurysm" (42%) followed by "intra-arterial thrombolysis or thrombectomy" (22%).[5] Endovascular treatment of BAVMs only had <5 articles in their top 100 article list and was not the main focus of their review.[5] In addition, the distribution of article types and levels of evidence was different when comparing our focused bibliometrics of endovascular treatment of BAVMs to their bibliometrics of neuro-interventional research. There were fewer comparative clinical trials

and systematic reviews or meta-analyses, but more case reports and case series in the field of endovascular treatment of BAVMs. This suggests that the endovascular treatment of BAVMs is still an emerging field that requires further clinical trials and higher-level evidence.

Another bibliometric study published by Ramos *et al*. in 2019 discussed the top 100 cited articles in central nervous system arteriovenous malformations (AVMs). However, their study had a slightly different focus compared to the present study as it included all research related to both brain and spinal AVMs, whilst the present review is focused specifically on the endovascular treatment of brain AVMs. In terms of article topics, 37 of their top 100 articles were on natural history/clinical features of AVMs rather than treatment, and of the 40 articles on treatment, only 11 were related to embolization and 7 were related to combined therapy.[115] In addition, it demonstrated narrower distributions in journals and countries of origin, with the Journal of Neurosurgery contributing to 39 articles, and the USA contributing to 70 articles.[115] In their study, there were only 29 out of 100 articles published after 2000, and hence, the authors concluded that high impact AVM research had been decreasing recently.[115] However, in our specific bibliographic analysis of the endovascular treatment of brain AVMs, the majority of articles ($n = 55$) were published after 2000 and this further demonstrates that it is an evolving field with active research interest.

As demonstrated in Table 1, a disparity was noted between the total citation numbers obtained via Web of Science and Google Scholar. This finding is consistent with several comparison studies of the Web of Science and Google Scholar platforms.[116,117] In general, Google Scholar provides a more comprehensive coverage but lower citation accuracy as well as fewer citations to group-authored articles. In contrast, the Web of Science included more citations from articles, letters, and editorials. Furthermore, the Web of Science only includes certain journals and has an emphasis on the quality rather than quantity of the coverage.[117] Since online citation databases are becoming a crucial source for research citations, there is a need for more studies to compare various online citation databases such as the Web of Science, Google Scholar, and Scopus platforms.

This citation analysis is inevitably bound by several limitations. Firstly, since the top 100 article list was established by using several search keywords, it was difficult to predict the impact of self-citations, incomplete citations, and citations in textbooks for this citation analysis. The amount of self-citations in general medical research is around 6%, which might be higher in this bibliometric analysis due to the relatively small number of authors contributing to the top 100 articles.[118] Incomplete citation is when authors use summarized information from articles without citing them. Secondly, this analysis may disadvantage the articles published in recent years due to the lack of time to accumulate impact and citations and may not demonstrate their true contribution to the development of endovascular treatment of BAVMs. We attempted to minimize this bias by examining the average citation per year as another marker of contemporary impact. A third limitation is the overall relatively low citation counts in endovascular treatment of BAVMs, compared to citation analyses in other medical fields, the top 100 citations in this field have a narrow range from 56 to 471. Combined with the previous points, this could result in the inclusion of articles with less true impact but published in earlier years and hence have the advantage to accrue citations. A fourth limitation is that this study only included articles published in English and may not recognize or capture the importance of articles published in other languages to the development of endovascular treatment of BAVMs. Lastly, Web of Science was the primary database utilized to obtain the list of most cited articles, and some impactful articles might be missed either because of the limitation in the combination of keyword search or the article was not included in the WoS database. We attempted to introduce citation counts from Google Scholar to mitigate this limitation but it comes with its own limitations and there could still be articles not indexed by either platform.

Conclusion

Our citation analysis contains a comprehensive list of the 100 most cited articles in the specialized and evolving field of endovascular treatment of BAVMs using extended keywords search in the database. It highlights some landmark papers as well as important authors, journals, and institutions in this field. ARUBA is one of the landmark papers in the treatment of BAVMs, and with its strengths and controversy, it facilitates further discussion and research in the field of BAVMs. Furthermore, the citation analysis provides a detailed overview of the current trend of research in the field of endovascular treatment of BAVMs, more specifically, the choice of embolization agents, evaluation of endovascular treatment to other treatment options or combined therapy, pathophysiology, novel endovascular technique and complication, and prognosis.

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Conflicts of interest
There are no conflicts of interest.

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