Anterior cervical surgery (ACS) owes its development to various pioneering individuals whose revolutionary works form key advances and guide current medical decisions. This bibliometric study aimed to identify, analyse and visualize the main features of the most-cited papers in ACS.

The citation count for the top 100 most-cited articles ranged from 148 to 1,197, and citations per year ranged from 3.1 to 89.8. The articles were published from 1958 to 2016, with the 2000s being the most active decade. There was an inverse correlation between the average citations per year since publication and article age.

The oldest as well as most-cited two articles were both published in 1958 by Smith and Robinson, and Cloward, respectively. In their studies, the authors individually described the technique of anterior cervical discectomy with fusion (ACDF).

The most popular keywords were: ‘fusion’ (22), ‘spine’ (20), ‘cervical spine’ (16), ‘complications’ (15), ‘arthrodasis’ (13), ‘interbody fusion’ (13), ‘bone morphogenetic protein’ (13), and ‘radiculopathy’ (12).

ACDF was the most frequent surgical procedure (80%), while cervical disc arthroplasty is of gradual greater impact.

The surgical techniques of ACDF have remained unaltered for over 60 years. More attempts are needed to promote its development.

Keywords: anterior cervical surgery; bibliometric analysis; VOSviewer

Introduction

Anterior cervical surgery (ACS) is one of the most commonly used cervical surgical approaches. It has been widely applied as a standard procedure for various cervical degenerative, traumatic, neoplastic, vascular, and infectious diseases since the 1950s. Generally, the commonly used ACS procedures include anterior cervical discectomy (ACD), anterior cervical disectomy with fusion (ACDF), anterior cervical corpectomy with fusion (ACCF), and cervical disc arthroplasty (CDA). Each technique has its proponents and inherent drawbacks mainly related to the adequacy of decompression of the spinal cord and nerve roots, maintenance of the stability of the spinal column, duration of the procedure and blood loss, and time required to recover from surgery and be discharged from the hospital. During the last 60 years, numerous studies have made considerable progress in the development of ACS. However, with an increase in the number of publications regarding ACS, gathering critical information from literature remains challenging. Thus, identifying the most impactful publications and trends in research hotspots is of great significance.

The bibliometric analysis applies multiple methods to qualitatively and quantitatively evaluate trends in research in a certain field. The number of citations per paper is one of the markers of scientific merit. A high number of citations indicates the influence of a paper on knowledge development. VOSviewer is a software tool for creating maps based on bibliographic data and for visualizing and exploring these maps. Though there have been such studies on spinal disorders and spinal image research as a whole, little is known about the most important literature on ACS and only a few studies have been visualized. Herein, we conducted a bibliometric analysis coupled with visualization tools using the Web of Science database to identify the top 100 most influential articles on ACS published in any journal from 1950 to 2021. This may help identify trends, focal points, and novelties that have defined ACS.
Materials and methods

Data source and search strategy

The Web of Science Core Collection database was comprehensively searched in May 2021 to identify the 100 most-cited articles focusing on ACS. The search strategy combined the following terms: “anterior cervical”, “anterior cervical surgery”, “anterior cervical spine surgery”, “anterior cervical approach”, or “cervical disc”. Only English-language articles were included for analysis. Conference papers were excluded. No limitation was imposed on publishing time. The cited articles were independently reviewed by two authors and discrepancies were resolved by consensus. The search results were ranked from the highest to lowest and the top 100 most-cited articles were obtained for publication trend analysis. The senior author reviewed each article to ensure its relevance to ACS.

Data analysis

The following basic information was extracted: title, authorship, year of publication, country and institution of publication, number of citations, citations per year, topic, and surgical types. All data were imported into Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) and analysed quantitatively and qualitatively. Every publication was assigned to the type of study. The type of study was categorized as diagnostic, therapeutic, prognostic, economic and basic studies, and reviews. Levels of evidence of original articles were classified based on criteria established by the Journal of Bone and Joint Surgery American Volume.14 Reviews were not assigned to a level of evidence. Moreover, VOSviewer (Leiden University, Leiden, Netherlands), a free Java program, was used for analysing and visualizing the co-occurrence of authors and co-occurrence of keywords. Meanwhile, the SPSS software version 24.0 (IBM Corporation, Armonk, NY, USA) was used for standard statistical analysis. Associations were investigated using Pearson or Spearman correlation tests. Differences between two groups were considered significant when the P-value was less than 0.05.

Results

Basic characteristics

The main characteristics of the top 100 most-cited studies are shown in Table 1. This search yielded 18,556 results, which were then sorted in descending order per the number of total citations. A total of 541 papers were cited 100 times or more, of which 327 precisely matched the search criteria. Collectively, the included studies covered the four major surgical types: ACD, ACDF, ACCF, and CDA. The top paper was cited 1,197 times, the 100th paper 148 times, and the median number of citations of the top 100 most-cited studies was 193.5, with a total of 25,810 citations. The number of citations since 2013 was between 0 and 128 (median, 12). Since publication, the average citations per year ranged from 3.1 to 89.8 (median, 10.9). Additionally, the number of pages in the included studies ranged from 3 to 30 (median, 7).

Among the top 100 most-cited papers, seven were systematic reviews, six were non-systematic reviews, and 87 were primary studies. Of the 87 original articles, 13 articles had level I evidence, 14 articles had level II evidence, 35 articles had level III evidence, 21 articles had level IV evidence, and four articles had level V evidence. Of note, articles with level IV evidence had the highest number of mean and total citations (402.3 citations per article, 8,448 citations, respectively).

Distribution of articles by years of publication

All studies were published between 1958 and 2016. The two oldest articles were by Cloward3 and Smith and Robinson4 which were both published in 1958. The most recent article was published in 2016 by James et al.15

About 85% of the top 100 most-cited papers were published after 1990, with the 2000s as the most active decade with 48 highly cited papers (Table 1; Fig. 1A). The most prolific year was 2007 with eight articles, followed by 2003 and 2005 with seven articles each. Moreover, there was an inverse correlation between average citations per year since publication and article age (r = −0.773; P < 0.05) (Fig. 1B).

Distribution of authors

Eighty-nine first authors contributed to the top 100 articles. Eight authors were represented multiple times in the top 100 articles (Table 2). Among these, Goffin J was regarded as the most productive first author with four articles (Article 21, 36, 48, 92 in Table 1), followed by Sasso RC with three articles (Article 77, 78, 82 in Table 1). VOSviewer map detailed through clusters the co-authorship relationships among all authors from the top 100 articles (Fig. 2). The main cluster contained prominent authors, including Heller JG, Vaccaro AR, Bohlman HH, and Hilibrand AS, gathering with 17 other authors. Another large cluster was formed by Goffin J and Casey A, gathering with 16 other different authors.

Distribution of articles by country and institution

There were 70 institutions from the correspondence addresses. Sixteen institutions were represented multiple times in the top 100 articles (Table 3). The top six institutions with the most productive articles were Case Western Reserve University, USA, Emory University, USA, Catholic University of Leuven, Belgium, Medical College of Wisconsin, USA, Osaka University, Japan, and Johns Hopkins University, USA.
Table 1. The top 100 cited articles on anterior cervical surgery

| Rank | Title                                                                                                                                                                                                 | First author | Total citations | Citations per year | Level of evidence |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|-----------------|---------------------|-------------------|
| 1    | The anterior approach removal of ruptured cervical disks                                                                                                                                             | Cloward, RB  | 1197            | 19.0                | IV                |
| 2    | The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion                                                                            | Smith, CW    | 1102            | 17.5                | IV                |
| 3    | Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis                                                                                 | Hilibrand, AS| 975             | 44.3                | IV                |
| 4    | A critical review of recombinant human bone morphogenetic protein-2 trials in spinal surgery: emerging safety concerns and lessons learned                                           | Carragee, EJ | 898             | 89.8                | IV                |
| 5    | Donor site morbidity after anterior iliac crest bone harvest for single-level anterior cervical disectomy and fusion                                                                              | Silber, JS   | 588             | 32.7                | IV                |
| 6    | Robinson anterior cervical disectomy and arthrodesis for cervical radiculopathy                                                                                                                    | Bohlman, HH  | 585             | 20.9                | IV                |
| 7    | Anterior cervical disectomy and fusion associated complications                                                                                                                                       | Fountas, KN  | 494             | 35.3                | IV                |
| 8    | Adverse effects associated with high-dose recombinant human bone morphogenetic protein-2 use in anterior cervical spine fusion                                                                 | Shields, LBE | 485             | 32.3                | IV                |
| 9    | Complications following autologous bone graft harvesting from the iliac crest and using the RIA: A systematic review                                                                                     | Dimitriou, R | 393             | 39.3                | NA                |
| 10   | Clinical and radiographic analysis of cervical disc arthroplasty compared with allograft fusion: a randomized controlled clinical trial                                                                | Mummameni, PV| 393             | 28.1                | I                 |
| 11   | Stabilization of the cervical spine by anterior fusion                                                                                                                                                 | Bailey, RW   | 378             | 6.2                 | IV                |
| 12   | Results of the prospective, randomized, controlled multicenter Food and Drug Administration investigational device exemption study of the ProDisc-C total disc replacement versus anterior disectomy and fusion for the treatment of 1-level symptomatic cervical disc disease | Murrey, D    | 351             | 29.3                | I                 |
| 13   | Comparison of BRYAN cervical disc arthroplasty with anterior cervical decompression and fusion                                                                                                        | Heller, JG   | 329             | 27.4                | I                 |
| 14   | Prevalence, complications, and hospital charges associated with use of bone-morphogenetic proteins in spinal fusion procedures                                                                     | Cahill, KS   | 317             | 26.4                | III               |
| 15   | Cervical laminectomy and dural ligament section for cervical spondylotic myelopathy                                                                                                                  | Benzel, EC   | 307             | 10.2                | III               |
| 16   | Anterior cervical fusion for degenerated or protruded disks - a review of 146 patients                                                                                                             | Gore, DR     | 303             | 8.2                 | III               |
| 17   | Effectiveness and harms of recombinant human bone morphogenetic protein-2 in spine fusion                                                                                                               | Fu, JW       | 296             | 37.0                | NA                |
| 18   | The results of anterior interbody fusion of the cervical spine                                                                                                                                         | Robinson, RA | 294             | 5.0                 | IV                |
| 19   | A review of the clinical side effects of bone morphogenetic protein-2                                                                                                                               | James, AW    | 293             | 58.6                | NA                |
| 20   | Increased swelling complications associated with off-label usage of rhBMP-2 in the anterior cervical spine                                                                                             | Smucker, JD  | 289             | 19.3                | III               |
| 21   | Long-term follow-up after interbody fusion of the cervical spine                                                                                                                                     | Goffin, J    | 288             | 16.9                | IV                |
| 22   | Late radiographic findings after anterior cervical fusion for spondylotic myeloradiculopathy                                                                                                           | BABA, H      | 285             | 10.2                | III               |
| 23   | Anterior cervical plating enhances arthrodesis after disectomy and fusion with cortical allograft                                                                                                      | Kaiser, MG   | 283             | 14.9                | III               |
| 24   | Anterior cervical decompression and arthrodesis for the treatment of cervical spondylotic myelopathy- two to seventeen-year follow-up                                                                 | Emery, SE    | 280             | 12.2                | III               |
| 25   | Kyphotic malalignment after anterior cervical fusion is one of the factors promoting the degenerative process in adjacent intervertebral levels                                                          | Katsurara, A | 265             | 13.3                | III               |
| 26   | Neck and shoulder pain after laminoplasty - A noticeable complication                                                                                                                                 | Hosono, N    | 263             | 10.5                | III               |
| 27   | Anterior surgery for cervical disc disease-part 1: treatment of lateral cervical disc herniation in 253 cases                                                                                           | Lunsford, LD | 262             | 6.4                 | III               |
| 28   | Anterior approaches to fusion of the cervical spine: a meta analysis of fusion rates                                                                                                                 | Fraser, JF   | 249             | 17.8                | III               |
| 29   | CS palsy after decompression surgery for cervical myelopathy                                                                                                                                         | Sakaora, H   | 249             | 13.8                | IV                |
| 30   | Assessment of adjacent-segment disease in patients treated with cervical fusion or arthroplasty: a prospective 2-year study                                                                            | Robertson, JT| 248             | 15.5                | II                |
| 31   | Early failure of long segment anterior cervical plate fixation                                                                                                                                        | Vaccaro, AR  | 248             | 10.8                | III               |
| 32   | Anterior cervical fusion and caspar plate stabilization for cervical trauma                                                                                                                           | Caspar, W    | 245             | 7.7                 | IV                |
| 33   | A comparative analysis of fusion rates and donor-site morbidity for autogeneic rib and iliac crest bone grafts in posterior cervical fusions                                                               | Sawin, PD    | 234             | 10.2                | III               |
| 34   | Strain on intervertebral discs after anterior cervical decompression and fusion                                                                                                                        | Fang, HSY    | 234             | 4.0                 | IV                |
| 35   | Intermediate follow-up after treatment of degenerative disc disease with the Bryan Cervical Disc Prosthesis: Single-level and bi-level                                                                  | Goffin, J    | 229             | 12.7                | II                |
| 36   | Anterior cervical interbody fusion using autogeneic and allogeneic bone graft substrate: a prospective comparative analysis                                                                           | Bishop, RC   | 228             | 9.1                 | II                |
| 37   | Subtotal corpectomy versus laminoplasty for multilevel cervical spondylotic myelopathy: A long-term follow-up study over 10 years                                                                          | Tannoury, CA | 225             | 32.1                | NA                |
| 38   | Complications with use of bone morphogenetic protein-2 (BMP-2) in spine surgery                                                                                                                   | Wada, E      | 224             | 11.2                | III               |
| 39   | Prospective, randomized, multicenter study of cervical arthroplasty: 269 patients from the Kinexflex|C artificial disc investigational device exemption study with a minimum 2-year follow-up                                                                 | Coric, D     | 223             | 22.3                | I                 |

(continued)
| Rank | Title                                                                 | First author | Total citations | Citations per year | Level of evidence |
|------|-----------------------------------------------------------------------|--------------|-----------------|--------------------|-------------------|
| 41   | Psychosocial predictors and correlates for chronic post-surgical pain (CPSP) – A systematic review | Hinrichs-Rocker, A | 216             | 18.0               | NA                |
| 42   | Safety and effectiveness of recombinant human bone morphogenetic protein-2 for spinal Fusion-A meta-analysis of individual-participant data | Simmonds, MC | 215             | 26.9               | NA                |
| 43   | Adjacent level intradiscal pressure and segmental kinematics following a cervical total disc arthroplasty-An in vitro human cadaveric model | Dmitriev, AE | 212             | 13.3               | V                 |
| 44   | A prospective, randomized, controlled cervical fusion study using recombinant human bone morphogenetic protein-2 with the CORNERSTONE-SR™ allograft ring and the ATLANTIS™ anterior cervical plate | Baskin, DS | 211             | 11.7               | I                 |
| 45   | Persistent iliac crest donor site pain: independent outcome assessment | Heary, RF | 210             | 11.1               | III               |
| 46   | The use of freeze-dried allograft bone for anterior cervical fusions | Zdeblick, TA | 209             | 7.0                | III               |
| 47   | Complications and mortality associated with cervical spine surgery for degenerative disease in the United States | Wang, MC | 199             | 14.2               | II                |
| 48   | Preliminary clinical experience with the Bryan Cervical Disc prosthesis | Goffin, J | 196             | 10.3               | II                |
| 49   | Complications of anterior cervical discectomy without fusion in 450 consecutive patients | Bertalanffy, H | 194 | 6.1 | IV |
| 50   | A prospective randomized multicenter clinical evaluation of an anterior cervical fusion cage | Hacker, RJ | 193 | 9.2 | I |
| 51   | Cervical radiculopathy | Carette, S | 192 | 12.0 | NA |
| 52   | Long-term clinical and radiographic outcomes of cervical disc replacement with the Prestige disc: results from a prospective randomized controlled clinical trial Presented at the 2009 Joint Spine Section Meeting Clinical article | Burkus, JK | 190 | 17.3 | I |
| 53   | Increased fusion rates with cervical plating for two-level anterior cervical discectomy and fusion | Wang, JC | 190 | 9.0 | III |
| 54   | Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery | Hillbrand, AS | 187 | 11.0 | I |
| 55   | Surgical-treatment for cervical spondylotic myelopathy | Ebersold, MJ | 185 | 7.1 | III |
| 56   | Cervical Spondylotic Myelopathy: The Clinical Phenomenon and the Current Pathobiology of an Increasingly Prevalent and Devastating Disorder | Kalsi-Ryan, S | 184 | 23.0 | NA |
| 57   | Prospective analysis of incidence and risk factors of dysphagia in spine surgery patients - Comparison of anterior cervical, posterior cervical, and lumbar procedures | Smith-Hammond, CA | 183 | 10.8 | II |
| 58   | Off-Label Use of Bone Morphogenetic Proteins in the United States Using Administrative Data | Ong, KL | 181 | 16.5 | II |
| 59   | Adverse swelling associated with use of rh-BMP-2 in anterior cervical discectomy and fusion: a case study | Perri, B | 181 | 12.9 | IV |
| 60   | Corpectomy Versus laminoplasty for multilevel cervical myelopathy - An independent matched-cohort analysis | Edwards, CC | 181 | 9.5 | III |
| 61   | Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling | Yoganandan, N | 181 | 9.1 | V |
| 62   | Hybrid multidirectional test method to evaluate spinal adjacent-level effects | Panjabi, MM | 180 | 12.9 | V |
| 63   | Increasing rates of cervical and lumbar spine surgery in the united-states,1979-1990 | Davish, H | 180 | 6.7 | II |
| 64   | A comparison of anterior cervical fusion, cervical laminectomy, and cervical laminoplasty for the surgical-management of multiple level spondylotic radiculopathy | Herkowitz, MN | 180 | 5.5 | III |
| 65   | Complications of anterior cervical fusion and fusion using recombinant human bone morphogenetic protein-2 | Vaidya, R | 179 | 12.8 | III |
| 66   | Central corpectomy for cervical spondylotic myelopathy-aconsecutive series with long-term follow-up evaluation | Saunders, RL | 179 | 6.0 | III |
| 67   | Outcome of patients treated for cervical myelopathy - A prospective, multicenter study with independent clinical review | Sampath, P | 178 | 8.5 | II |
| 68   | Analysis of harvest morbidity and radiographic outcome using autograft for anterior cervical fusion | Schnee, CL | 177 | 7.4 | III |
| 69   | Neurologic complications of surgery for cervical compression myelopathy | Yonenobu, K | 177 | 5.9 | III |
| 70   | Influence of an artificial cervical joint compared with fusion on adjacent-level motion in the treatment of degenerative cervical disc disease | Wigfield, C | 175 | 9.2 | II |
| 71   | Multilevel anterior cervical corpectomy and fibular allograft fusion for cervical myelopathy | Macdonald, RL | 175 | 7.3 | IV |
| 72   | A comprehensive review of the safety profile of bone morphogenetic protein in spine surgery | Benglis, D | 174 | 13.4 | NA |
| 73   | Anterior cervical fusion: Outcome analysis of patients fused with and without anterior cervical plates | Connolly, PJ | 174 | 7.0 | III |
| 74   | The results of anterior interbody fusion of the cervical spine. Review of ninety-three consecutive cases | Riley, LH | 174 | 3.3 | III |
| 75   | Cervical kyphosis and myelopathy. Treatment by anterior corpectomy and strut-grafting | Zdeblick, TA | 172 | 5.4 | III |
| 76   | Heterotropic ossification in total cervical artificial disc replacement | Mehren, C | 170 | 11.3 | II |
| 77   | Early reconstruction failures after multilevel cervical corpectomy | Sasso, RC | 170 | 9.4 | III |
Table 1. (continued)

| Rank | Title                                                                 | First author | Total citations | Citations per year | Level of evidence |
|------|-----------------------------------------------------------------------|--------------|-----------------|--------------------|-------------------|
| 78   | Results of Cervical Arthroplasty Compared with Anterior Discectomy and Fusion: Four-Year Clinical Outcomes in a Prospective, Randomized Controlled Trial | Sasso, RC   | 167             | 16.7               | I                 |
| 79   | National trends in surgical procedures for degenerative cervical spine disease: 1990-2000 | Patil, PG    | 166             | 10.4               | II                |
| 80   | Laminoplasty versus subtotal corpectomy. A comparative study of results in multisegmental cervical spondylotic myelopathy | Yonenobu, K  | 165             | 5.7                | III               |
| 81   | Full-endoscopic cervical posterior foraminotomy for the operation of lateral disc herniations using 5.9-mm endoscopes - A prospective, randomized, controlled study | Ruettten, S  | 164             | 12.6               | I                 |
| 82   | Artificial disc versus fusion - A prospective, randomized study with 2-year follow-up on 99 patients | Sasso, RC    | 164             | 11.7               | I                 |
| 83   | Neurologic complications of anterior cervical interbody fusion | Flynn, TB    | 164             | 4.2                | II                |
| 84   | Influence of anterior cervical plate design on dysphagia - A 2-year prospective longitudinal follow-up study | Lee, MJ      | 163             | 10.2               | II                |
| 85   | Complications in spine surgery A review                               | Nasser, R    | 162             | 14.7               | NA                |
| 86   | Dysphagia after anterior cervical decompression and fusion - Prevalence and risk factors from a longitudinal cohort study | Riley, LH    | 162             | 10.1               | III               |
| 87   | Treatment of neoplastic spinal cord compression: results of a prospective study | Sundaresan, N | 162          | 5.4                | IV                |
| 88   | Cervical Spondylotic Myelopathy                                      | Tracy, JA    | 159             | 14.5               | NA                |
| 89   | Anterior discectomy and fusion for painful cervical disc disease - A report of 50 patients with an average follow-up of 21 years | Gore, DR     | 158             | 6.9                | IV                |
| 90   | Long-lasting cervical radicular pain managed with surgery, physiotherapy, or a cervical collar - A prospective, randomized study | Persson, LCG | 158             | 6.6                | I                 |
| 91   | Assessment of the minimum clinically important difference in pain, disability, and quality of life after anterior cervical discectomy and fusion | Parker, SL   | 156             | 19.5               | I                 |
| 92   | Long-term results after anterior cervical fusion and osteosynthetic stabilization for fractures and/or dislocations of the cervical spine | Goffin, J    | 156             | 6.0                | IV                |
| 93   | Subsidence of stand-alone cervical cages in anterior interbody fusion: warning | Gercek, E    | 155             | 8.6                | IV                |
| 94   | Cervical spondylotic myelopathy: A common cause of spinal cord dysfunction in older persons | Young, WF    | 155             | 7.4                | NA                |
| 95   | Increased fusion rates with cervical plating for three-level anterior cervical discectomy and fusion | Wang, JC     | 154             | 7.7                | III               |
| 96   | Operations for cervical spondylotic myelopathy. A comparison of the results of anterior and posterior procedures | Hukuda, S    | 154             | 4.3                | III               |
| 97   | Biomechanical testing of an artificial cervical joint and an anterior cervical plate | DiAngelo, DJ  | 153            | 8.5                | V                 |
| 98   | Anterior interbody fusion for severe cervical disc degeneration | DePalma, AF  | 153             | 3.1                | IV                |
| 99   | Airway complications associated with surgery on the anterior cervical spine | Sagi, HC     | 149             | 7.8                | III               |
| 100  | Is autograft the gold standard in achieving radiographic fusion in one-level anterior cervical discectomy and fusion with rigid anterior plate fixation? | Samartzis, D | 148             | 9.3                | III               |

Fig. 1 Overview of the publication year distribution. (A) Number and citations of the top 100 most-cited articles per decade. (B) Correlation between article age and average citations per year since publication.
Concerning country and region of origin, the top 100 articles originated from seven different countries, with the United States contributing 74% of all articles and 78.4% of all citations. Moreover, articles from Europe were represented by four countries (Germany, United Kingdom, Belgium, and Sweden) with 14 articles and 3,033 citations. Asia was only represented by articles from Japan (nine papers; 2,012 citations). However, Latin America, Oceania, and Africa had no papers included (Fig. 3).

**Distribution of published journals**

All articles were published in 22 different journals, with the top three journals publishing 57% of the articles (Table 4). The most contributed journal was *Spine* with 38 papers, followed by the *Journal of Bone and Joint Surgery American Volume* with 10 papers and the *Journal of Neurosurgery* with nine papers. Naturally, *Spine* had the highest number of citations (8,545 citations). However, the *Journal of Bone and Joint Surgery American Volume* had the highest number of mean citations (437.4 citations), followed by *Spine Journal* (413.8 citations).

**Distribution of study types and topics**

The most common study types were reports of ‘therapeutic’ (n = 73), followed by ‘prognostic’ (n = 9), non-systematic reviews (n = 7), systematic reviews (n = 6), ‘basic’ (n = 4), and ‘diagnostic’ (n = 1) (Table 5). Concerning topics, most articles were assigned to more than one type of surgery. Overall, ACDF was the most frequent surgical procedure. Eighty per cent (80/100) of the top 100 articles related to ACDF, while only seven papers applied ACD as the research object. Further, 28 and 15 papers were assigned to ACCF and CDA, respectively.

Moreover, keywords were analysed using a co-occurrence network analysis tool in the VOSViewer software with a minimum number of keyword occurrences of five (Fig. 4). A total of 32 keywords were identified and classified into three clusters: ‘surgical procedures’, ‘disorders and symptoms’, and ‘complications’. Overall, the most popular keywords were: ‘fusion’ (22), ‘spine’ (20),

| First author | No. of articles | Total citations |
|--------------|----------------|----------------|
| Goffin, J    | 4              | 869            |
| Hilibrand, AS| 2              | 1162           |
| Sasso, RC    | 3              | 501            |
| Gore, DR     | 2              | 461            |
| Zdeblick, TA | 2              | 381            |
| Wang, JC     | 2              | 344            |
| Yonenobu, K  | 2              | 342            |
| Riley, LH    | 2              | 336            |

### Table 2. First authors with multiple publications

**Fig. 2** VOSviewer co-authorship map illustrating author density and the existence of clusters among all authors of the 100 most-cited articles.
on ACS has progressed significantly since its inception, especially in recent years.\textsuperscript{5,16} Our study revealed a steady increase in the number of ACS publications, with 62% of highly cited papers published in the last two decades (Fig. 1A). This trend demonstrates that ACS research has progressed rapidly and attracted more attention, which may be due to the global increase in the incidence of refractory cervical degenerative disc disease (CDDD).\textsuperscript{5,17}

The Global Burden of Disease 2015 study revealed that the incidence of neck pain has increased yearly over the past 25 years, and that the number of years lived with disability caused by neck pain has increased by 21% from 2005 to 2015, ranking fourth in all 315 diseases after being combined with low back pain.\textsuperscript{18} Moreover, the emergence of CDA, a motion-preserving and highly cost-effective surgical procedure, made a considerable contribution to the development of ACS.\textsuperscript{19} However, the research has been extensive and relatively non-conforming, and analysis of research hotspots and trends is largely lacking. Thus, identifying classic works may provide insight into the history, development, and current state of ACS and help to capture emerging themes and future tendencies of ACS.

The oldest as well as most-cited two articles in our study were both published in the United States in 1958.\textsuperscript{3,4} Interestingly, in their studies, Smith and Robinson, and Cloward individually described a novel anterior approach to the cervical spine for the removal of cervical intervertebral discs, which is currently known as ACDF and its usage in 14 and 47 patients, respectively. Generally speaking, Smith and Robinson first described the ACDF technique in 1955,\textsuperscript{2} and Cloward was the first to publish the approach

### Discussion

To the best of our knowledge, the current study is the first to analyse the quality and quantity of studies using bibliometric analysis and visualization tools in ACS. Research...
in the neurosurgical literature in 1958. Compared with Smith and Robinson’s approach, cosmetic horizontal skin crease incision is applied in Cloward’s approach, and a trephine, instead of pituitary rongeurs and curettes, is used to deal with the disc space.3,4,20 More importantly, the final results of these two articles showed that ACDF could completely remove both soft tissue and bony elements encroaching the nerve roots or the spinal cord and relieve symptoms safely and effectively. Until now, ACDF has been regarded as the original form of ACS and a classic gold standard.1,6,16,21 The 80% attendance rate of ACDF in the results of this current study proves this point as well. In the current study, 80% of the top 100 articles were related to ACDF, which confirms the above results. However, surgical techniques of ACDF have remained unaltered for over 60 years. Although this reflects the recognition of its safety and efficacy, it also suggests that more attempts are needed to promote its development.

Regarding the distribution of countries, we found that the United States dominated (74%) the top 100 most-cited papers when compared with other countries (Fig. 3). This can be explained by several potential reasons. First, as previously mentioned, ACS originated in the US. Of the first 11 articles in our list, 10 were conducted by US institutions. Second, ACS has been one of the most commonly used cervical spine surgeries in North America for the past few decades, and its application is still soaring. In terms of ACDF alone, a population-based database analysis showed that the 15 years between 1990 and 2014 witnessed a significant increase in the number of ACDF procedures in the United States from about 60,000 (1990–1994) to over 450,000 (2000–2004).21 In a recent investigation, a total of 1,212,475 ACDF cases were identified between 2004 and 2014 in the US,22 and this procedure now accounts for over 80% of all cervical spine surgeries.1 Our research also showed that four of the six most productive institutions and six of the eight most productive authors were

**Table 4.** Journals with multiple publications

| Journal                                | No. of articles | Total citations | Mean citations |
|----------------------------------------|-----------------|-----------------|---------------|
| Spine                                  | 38              | 8545            | 224.9         |
| Journal of Bone and Joint Surgery      | 10              | 4374            | 437.4         |
| American Journal of Neurorsurgery       | 9               | 2809            | 312.1         |
| Journal of Neurosurgery-Spine          | 7               | 1621            | 231.6         |
| Journal of Spinal Disorders            | 7               | 1489            | 212.7         |
| Neurosurgery                           | 7               | 1436            | 205.1         |
| Spine Journal                          | 4               | 1655            | 413.8         |
| European Spine Journal                 | 3               | 599             | 199.7         |
| Annals of Internal Medicine            | 2               | 511             | 255.5         |
| Clinical Biomechanics                  | 2               | 361             | 180.5         |

*Continued by Journal of Spinal Disorders & Techniques (2002–2015) and Clinical Spine Surgery (2016–present).

**Table 5.** Distribution of study types

| Study type       | No. of articles | Total citations | Mean citations |
|------------------|-----------------|-----------------|---------------|
| Original study   |                 |                 |               |
| Diagnostic       | 1               | 187             | 187.0         |
| Therapeutic      | 73              | 18594           | 254.7         |
| Prognostic       | 9               | 2741            | 304.6         |
| Economic         | 0               | 0               | 0             |
| Basic Review     | 4               | 726             | 181.5         |
| Review           |                 |                 |               |
| Systematic       | 6               | 2180            | 363.3         |
| Non-systematic   | 7               | 1382            | 197.4         |

**Fig. 4** Keyword analysis. (A) Network visualization map showing cluster analysis of keywords associated with ACS. (B) Overlay visualization map showing trends of keyword frequency over time. Colours were assigned according to the average year in which keywords appeared in articles.

Note. ACS, anterior cervical surgery.
from the US (Table 3; Fig. 2). Of note, Japan was the second most productive country in the current analysis (n = 9). Out of these nine papers, seven were related to the procedure of ACCF. This could be due to the higher incidence rate of ossification of the posterior longitudinal ligament in East Asia. It often requires a larger resection and decompression range, which is a unique advantage and major surgical indication of ACCF.

Concerning research topics and hotspots, half of the most popular keywords were related to fusion. Consequently, approaches promoting bony fusion have been continuously reported and received great attention, such as bone morphogenetic protein (BMP) with 11 papers and anterior cervical plating with nine papers in our analysis. Herein, the article by Carragee et al25 with the highest average number of citations and the most recent article by James et al15 were both reviews involving the application and complications of BMP-2 on ACDF. However, the effect of BMP-2 on improving the fusion rate in spinal surgery is controversial. Moreover, three highly cited studies in our list warned against using high-dose BMP-2 in anterior cervical fusion, especially due to its life-threatening cervical spine swelling. Contrary to BMP, previous literature demonstrated that the use of anterior cervical plating could enhance arthrodesis. However, the influence of the plate on the prevertebral soft tissue and the consequent dysphagia have raised concerns. Another highly cited article by Lee et al indicated that a smaller and smoother profile plate reduces the incidence of dysphagia after ACDF. Furthermore, some recent high-level evidence articles revealed that zero-profile spacer was better than the cage-plate in terms of dysphagia.

In terms of research trends, the emergence and development of CDA were noted (Fig. 4). Our overlay visualization map clearly illustrates the rise of ‘arthroplasty’ in the 2000s. Nevertheless, the initial philosophy of CDA was firstly proposed by Fernström in the 1960s, but due to the serious subsidence and displacement of the prosthesis, and the immobility of the replacement level, the usage and promotion of CDA have been greatly restricted. Until it was reintroduced in Europe (Bryan, Prestige ST) in the late 1990s, and the US Food and Drug Administration (FDA) approved the first two artificial cervical disc prostheses (Prestige ST, Prodisc-C) in 2007, CDA was then gradually spread globally. Most of the early studies of CDA were randomized controlled trials (Table 1). This explains why the level of evidence in CDA-related studies is generally higher, and more than half of the articles with level I evidence (7/13) in our list were from CDA. More importantly, although CDA is a contemporary research hotspot, the surgical indications of CDA are relatively narrow and the surgical technique is more complex. Therefore, it is inappropriate to completely consider CDA as an alternative to another ACS.

As a bibliometric citation analysis, our study has several limitations. Initially, the majority of the top 100 cited papers were published after 1990. Consistent with previous bibliometric studies, older articles are likely to accrue more citations due to the ‘cumulative effect’. Nonetheless, our study revealed that annual citation rate and article age were negatively correlated (Fig. 1B). This resulted in a higher average citation per year of recent papers compared to older ones in the top 100 most-cited ACS articles. Therefore, the annual citation rate might be a better citation impact marker of the literature to a certain extent. Contrary to the first point, current articles affected by the phenomenon of ‘obliteration by incorporation’ may less frequently cite classic papers, resulting in their absorption into the body of current knowledge. Finally, citation count from a single database (Web of Science Core Collection) may not be the sole marker of an article’s scientific quality and influence, which should be critically considered in the future.

Conclusion
The current study attempted to develop a resource with detailed information on the top 100 most-cited articles on ACS. It demonstrated essential advances in ACS and identified influential authors, institutions, countries, and journals that had made outstanding contributions in this field. Generally, the United States, as the birthplace of ACS, has the most in-depth and influential research and has made the most prominent contribution to the development of ACS. Although the most common ACS is ACDF, CDA is of gradual greater impact. These insights into priorities and trends of the research could help future academic pursuits.

AUTHOR INFORMATION
1Department of Orthopedic Surgery, West China Hospital, Sichuan University, Chengdu, China.
2West China School of Nursing, Sichuan University/ Department of Anesthesia and Operation Center, West China Hospital, Sichuan University, Chengdu, China.
3These authors contributed equally to this work and should be considered co-first authors.

Correspondence should be sent to: Hao Liu, Department of Orthopedic Surgery, West China Hospital, Sichuan University, No. 37 Guo Xue Xiang, Chengdu, Sichuan, 610041, China.
Email: dr.liuhaoo304@hotmail.com or 
Correspondence should be sent to: Ying Hong, West China School of Nursing, Sichuan University/ Department of Anesthesia and Operation Center, West China Hospital, Sichuan University, No. 37 Guo Xue Xiang, Chengdu, Sichuan, 610041, China.
Email: hongyin518@126.com
ICMJE CONFLICT OF INTEREST STATEMENT
The authors declare no conflict of interest relevant to this work.

FUNDING STATEMENT
No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

OPEN ACCESS
© 2021 The author(s)
This article is distributed under the terms of the Creative Commons Attribution-Non Commercial 4.0 International (CC BY-NC 4.0) licence (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed.

REFERENCES
1. Liu CY, Zygomartakis CC, Yoon S, et al. Trends in utilization and cost of cervical spine surgery using the National Inpatient Sample Database, 2001 to 2013. Spine 2017;42:E506–E913.
2. Robinson RA, Smith GW. Anterior lateral disc removal and interbody fusion for cervical disc syndrome. Bull Johns Hopkins Hosp 1955;96:224–224.
3. Cloward RB. The anterior approach for removal of ruptured cervical disks. J Neurosurg 1958;15:602–617.
4. Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. J Bone Joint Surg (Am) 1958;40-A:602–624.
5. Kavanagh RG, Butler JS, O’Byrne JM, Poynton AR. Operative techniques for cervical radiculopathy and myelopathy. Adv Orthop 2012;2012:794087.
6. Fraser JF, Härtl R. Anterior approaches to fusion of the cervical spine: a metanalysis of fusion rates. J Neurosurg Spine 2007;6:298–303.
7. Caspar W, Barbier DD, Klara PM. Anterior cervical fusion and Caspar plate stabilization for cervical trauma. Neurosurgery 1989;25:491–501.
8. Theodore N. Degenerative cervical spondylisis. N Engl J Med 2020;383:159–168.
9. Garfield E. Citation analysis as a tool in journal evaluation. Science 1972;178:477–479.
10. Moed HF. New developments in the use of citation analysis in research evaluation. Arch Immunol Ther Exp (Warsz) 2010;58:523–538.
11. van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 2010;84:523–538.
12. Badhiwala JH, Nassiri F, Witw CD, et al. Highly cited works in spinal disorders: the top 100 most cited papers published in spine journals. Spine 2018;43:1746–1755.
13. Das JP, Aheme E, Kavanagh E. Imaging of the spine: a bibliometric analysis of the 100 most-cited articles. Spine 2019;44:1593–1598.
14. Marx RG, Wilson SM, Swiontkowski MF. Updating the assignment of levels of evidence. J Bone Joint Surg (Am) 2015;97-A:1–2.
15. James AW, LaChaud G, Shen J, et al. A review of the clinical side effects of bone morphogenetic protein-2. Tissue Eng Part B Rev 2016;22:284–297.
16. Sugawara T. Anterior cervical spine surgery for degenerative disease: a review. Neural Med Chir (Tokyo) 2015;55:540–546.
17. Zhuang L, Wang L, Xu D, Wang Z, Liang R. Association between excessive smartphone use and cervical disc degeneration in young patients suffering from chronic neck pain. J Orthop Sci 2021;26:110–115.
18. Vos T, Allen C, Arora M, et al; GBD 2015 Disease and Injury Incidence and Prevalence Collaborators. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. Lancet 2016;388:1545–1622.
19. Mummaneni PV, Burkus JK, Haid RW, Traynelis VC, Zdeblick TA. Clinical and radiographic analysis of cervical disc arthroplasty compared with allograft fusion: a randomized controlled trial. J Neurosurg Spine 2007;6:198–209.
20. Baker ADL. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. Classic Papers in Orthopaedics, London; Springer-Verlag, 2014:293–295.
21. Marawar S, Girardi FP, Sama AA, et al. National trends in anterior cervical fusion procedures. Spine 2010;35:1454–1459.
22. Perez-Roman RJ, Luther EM, McCarthy D, et al. National trends and correlates of dysphagia after anterior cervical discectomy and fusion surgery. Neurosurgery 2021;84:147–154.
23. Matsunaga S, Sakou T. Ossification of the posterior longitudinal ligament of the cervical spine: etiology and natural history. Spine 2012;37:E390–E394.
24. Mizuno J, Nakagawa H. Ossified posterior longitudinal ligament: management strategies and outcomes. Spine J 2006;6:2825–2885.
25. Carragee EJ, Hurwitz EL, Weiner BK. A critical review of recombinant human bone morphogenetic protein-2 trials in spinal surgery: emerging safety concerns and lessons learned. Spine J 2011;11:477–491.
26. Guppy KH, Paxton EW, Harris J, Alvarez J, Bernbeck J. Does bone morphogenetic protein change the operative nonunion rates in spine fusions? Spine 2014;39:1831–1839.
27. Shields LB, Raque GH, Glassman SD, et al. Adverse effects associated with high-dose recombinant human bone morphogenetic protein-2 use in anterior cervical spine fusion. Spine 2006;31:542–547.
28. Vaidya R, Carp J, Sethi A, Bartol S, Craig J, Les CM. Complications of anterior cervical discectomy and fusion using recombinant human bone morphogenetic protein-2. Eur Spine J 2007;16:1257–1265.
29. Smucker JD, Rhee JM, Singh K, Yoon ST, Heller JG. Increased swelling complications associated with off-label usage of rhBMP-2 in the anterior cervical spine. Spine 2006;31:2813–2819.
30. Kaiser MG, Haid RW Jr, Subach BR, Barnes B, Rodts GE Jr. Anterior cervical plating enhances arthrodesis after discectomy and fusion with cortical allograft. Neurosurgery 2002;50:229–236.
31. Wang JC, McDonough PW, Endow KK, Delamarter RB. Increased fusion rates with cervical plating for two-level anterior cervical discectomy and fusion. Spine 2000;25:41–45.
32. Wang JC, McDonough PW, Kanim LE, Endow KK, Delamarter RB. Increased fusion rates with cervical plating for three-level anterior cervical discectomy and fusion. Spine 2001;26:643–646.
33. Fountas KN, Kapsalaki EZ, Nikolakakos LG, et al. Anterior cervical discectomy and fusion associated complications. Spine 2007;32:2302–2317.
34. Riley LH III, Skolasky RL, Albert TJ, Vaccaro AR, Heller JG. Dysphagia after anterior cervical decompression and fusion: prevalence and risk factors from a longitudinal cohort study. Spine 2005;30:2564–2569.
35. Lee MJ, Bazar R, Furay CG, Yoo J. Influence of anterior cervical plate design on Dysphagia: a 2-year prospective longitudinal follow-up study. J Spinal Disord Tech 2005;18:406–409.
36. Nambiar M, Phan K, Cunningham JE, Yang Y, Turner PL, Mobbs R. Locking stand-alone cages versus anterior plate constructs in single-level fusion for degenerative cervical disease: a systematic review and meta-analysis. *Eur Spine J* 2017;26:2258–2266.

37. Xiao S, Liang Z, Wei W, Ning J. Zero-profile anchored cage reduces risk of postoperative dysphagia compared with cage with plate fixation after anterior cervical disectomy and fusion. *Eur Spine J* 2017;26:975–984.

38. Fernström U. Arthroplasty with intercorporal endoprosthesis in herniated disc and in painful disc. *Acta Chir Scand Suppl* 1966;357:15–19.

39. Reitz H, Joubert MJ. Intractable headache and cervico-brachialgia treated by complete replacement of cervical intervertebral discs with a metal prosthesis. *S Afr Med J* 1964;38:881–884.

40. Goffin J, Van Calenbergh F, van Loon J, et al. Intermediate follow-up after treatment of degenerative disc disease with the Bryan Cervical Disc Prosthesis: single-level and bi-level. *Spine* 2003;28:2673–2678.

41. Goffin J, Casey A, Kehr P, et al. Preliminary clinical experience with the Bryan Cervical Disc Prosthesis. *Neurosurgery* 2002;51:840–845.

42. Wigfield C, Gill S, Nelson R, Langdon I, Metcalf N, Robertson J. Influence of an artificial cervical joint compared with fusion on adjacent-level motion in the treatment of degenerative cervical disc disease. *J Neurosurg* 2002;96:17–21.

43. Murrey D, Janssen M, Delamarter R, et al. Results of the prospective, randomized, controlled multicenter Food and Drug Administration investigational device exemption study of the ProDisc-C total disc replacement versus anterior disectomy and fusion for the treatment of 1-level symptomatic cervical disc disease. *Spine* 2009;34:275–286.

44. Heller JG, Sasso RC, Papadopoulos SM, et al. Comparison of BRYAN cervical disc arthroplasty with anterior cervical decompression and fusion: clinical and radiographic results of a randomized, controlled, clinical trial. *Spine* 2009;34:101–107.

45. Coric D, Nunley PD, Gayer RD, et al. Prospective, randomized, multicenter study of cervical arthroplasty: 269 patients from the Kineflex(C) artificial disc investigational device exemption study with a minimum 2-year follow-up: clinical article. *J Neurosurg Spine* 2011;15:348–358.

46. Burkus JK, Haid RW, Traynelis VC, Mummaneni PV. Long-term clinical and radiographic outcomes of cervical disc replacement with the Prestige disc: results from a prospective randomized controlled clinical trial. *J Neurosurg Spine* 2016;13:308–318.

47. Sasso RC, Anderson PA, Riew KD, Heller JG. Results of cervical arthroplasty compared with anterior disectomy and fusion: four-year clinical outcomes in a prospective, randomized controlled trial. *J Bone Joint Surg [Am]* 2011;93-A:1684–1692.

48. Sasso RC, Smucker JD, Hacker RJ, Heller JG. Artificial disc versus fusion: a prospective, randomized study with 2-year follow-up on 99 patients. *Spine* 2007;32:2933–2940.

49. Health Quality Ontario. Cervical artificial disc replacement versus fusion for cervical degenerative disc disease: a health technology assessment. *Ont Health Technol Assess Ser* 2019;19:e1–e223.

50. Zhang Y, Wumaier M, He D, Xiao B, Zhang J. The 100 top-cited articles on spinal deformity: a bibliometric analysis. *Spine* 2020;45:275–283.

51. Garfield E. 100 citation classics from the *Journal of the American Medical Association*. *JAMA* 1987;257:52–59.