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# Bradford's law: identification of the core journals for neurosurgery and its subspecialties

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**OBJECTIVE** Bradford's law describes the scatter of citations for a given subject or field. It can be used to identify the most highly cited journals for a field or subject. The objective of this study was to use currently accepted formulations of Bradford's law to identify core journals of neurosurgery and neurosurgical subspecialties.

**METHODS** All original research publications from 2009 to 2013 were analyzed for the top 25 North American academic neurosurgeons from each subspecialty. The top 25 were chosen from a ranked career h-index list identified from previous studies. Egghe's formulation and the verbal formulation of Bradford's law were applied to create specific citation density zones and identify the core journals for each subspecialty. The databases were then combined to identify the core journals for all of academic neurosurgery.

**RESULTS** Using Bradford's verbal law with 4 zone models, the authors were able to identify the core journals of neurosurgery and its subspecialties. The journals found in the most highly cited first zone are presented here as the core journals. For neurosurgery as a whole, the core included the following journals: *Journal of Neurosurgery*, *Neurosurgery*, *Spine*, *Stroke*, *Neurology*, *American Journal of Neuroradiology*, *International Journal of Radiation Oncology Biology Physics*, and *New England Journal of Medicine.* The core journals for each subspecialty are presented in the manuscript.

**CONCLUSIONS** Bradford's law can be used to identify the core journals of neurosurgery and its subspecialties. The core journals vary for each neurosurgical subspecialty, but *Journal of Neurosurgery* and *Neurosurgery* are among the core journals for each neurosurgical subspecialty.

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**KEY WORDS** Bradford's law; bibliometrics; h-index; citation analysis; core journals; Scopus; neurosurgery; subspecialties

Physicians use a variety of resources to remain current in their field of interest, including conferences, electronic media, periodicals, peer-reviewed journals, and textbooks.[22] Historically, peer-reviewed journals have been used by physicians to maintain expertise in their particular fields, but this has become increasingly more difficult given the exponential expansion of scientific literature, which is currently doubling in size every 7 years.[20,27,28] Clinical researchers are faced with the increasing challenge of staying up-to-date on standards of practice and cutting-edge research. All neurosurgical subspecialties benefit from discoveries made in other disciplines, such as molecular biology, neurology, oncology, and radiology, and these discoveries may be more pertinent for one subspecialty than another. For this reason, it would be advantageous for researchers to know which scientific journals, including nonneurosurgical journals, contain the most useful information for general and subspecialty neurosurgeons.

In 1934, Samuel C. Bradford first described how information was scattered for a given subject based on the distribution of references.[3] Bradford discovered that when equally dividing all references in a given subject into 3 groups, or zones, the citations for the first zone would come from a small "core" group of journals. The second zone would require more journals to achieve the same number of citations, and the third zone exponentially more than the second. In moving from Zone 1 to Zone 3 there is a

**ABBREVIATION** IF = impact factor.
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"diminishing productivity" described by Bradford, which has become known as Bradford's law of scattering, or Bradford's distribution. Figure 1 depicts a graphical representation of Bradford's law. Hjørland and Nicolaisen[10] noted that Bradford's law has influenced the methodology of building collections, selecting journals indexed in bibliographies, measuring the coverage of bibliographies, solving practical problems related to information seeking and retrieval, and arguing for updated organization of bibliographical work and scientific documentation. Bradford's law of scattering, Lotka's law of scientific productivity, and Zipf's law of word occurrence are the 3 most commonly used principles in bibliometrics.

Core journals have been identified in many fields by using Bradford's law of scattering, including environmental and occupational health,[23] nursing,[24] physical and rehabilitation medicine,[7] physical therapy,[6] physics,[26] and science.[4] In 2013, Madhugiri et al.[19] were the first to apply Bradford's law of scattering to identify core journals within the field of neurosurgery. They sampled all journal references from the 11 top neurosurgical journals based on impact factor (IF) over a 3-month period, excluding special and focused editions in which many articles about a single specific topic were published. They were able to fit Bradford's law into 3 zones (p) for a total of 182 journals, with the 6 core journals within Zone 1 being *Journal of Neurosurgery, Neurosurgery, Spine, Acta Neurochirurgica, Stroke,* and *Journal of Neurotrauma*.[19] Additionally, in 2014, we applied Bradford's law to the field of pediatric neurosurgery.[15] We examined all published articles in a 5-year period from the top 25 North American pediatric neurosurgeons based on h-index, as well as the top 25 European pediatric neurosurgeons. Using Bradford's law of scattering, we were able to identify 9 core journals with a Bradford's multiplier of 4. These journals are as follows: *Journal of Neurosurgery, Neurosurgery, Epilepsia, Child's Nervous System, Pediatric Neurosurgery, Neurology, Journal of Clinical Oncology, Cancer Research,* and *New England Journal of Medicine*.[15]

We recently created productivity profiles for nearly all neurosurgical researchers in the US.[14] Many of these bibliometric indices, particularly the h-index, have been widely applied in neurosurgery.[1,8,11–14,17,25,29] Using this database, we examined 6 different neurosurgery subspecialties: neurosurgical oncology, peripheral nerve, skull base, spine, stereotactic and functional, and vascular. We identified the top 25 North American neurosurgeons in each of these subspecialties based on their h-index. By applying Bradford's law to journal articles that were referenced by each of those neurosurgeons over a 5-year period (2009–2013), we identified the core journals for each of the neurosurgical subspecialties. These databases were then combined, including the pediatric neurosurgery database previously reported,[30] to create citation density zones and identify the core journals for neurosurgery overall.

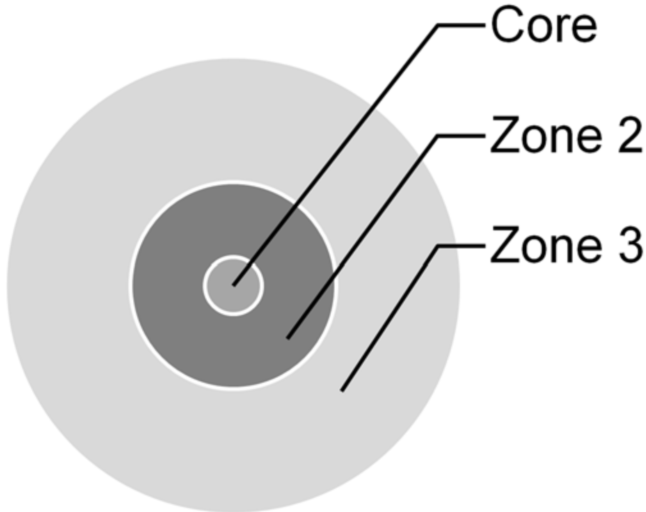


**FIG. 1.** Graphical depiction of Bradford's law. Each zone carries an equal number of citations, and zone size is equal to the number of journals in that zone.

## Methods

### Study Population and Data Retrieval

Recently we identified the top North American academic neurosurgeons as ranked by h-index.[14] From this bibliometric database we identified the top 25 academic neurosurgeons from each of the Society of Neurological Surgeons (SNS)—and Committee on Advanced Subspecialty Training (CAST)–recognized subspecialties, in addition to skull base, and we used these to develop subspecialty databases of journal citation data. In 2014 we described our method of data retrieval and analysis as applied to pediatric neurosurgery for the application of Bradford's law to identify the core journals of pediatric neurosurgery.[30] The methods used herein are identical. Scopus was used to identify all original research journal articles (excluding review articles, editorial letters, and so on) for each neurosurgeon, spanning the years 2009–2013. Every article for each author was evaluated to compile data describing the journal publication counts and journal citation counts. Self-citation data were retrieved from Scopus' built-in search and filter functions.

Every effort was made in our database to exclude intradepartmental duplications of publications for those researchers who may share authorship. The researcher with the highest h-index received credit for all publications authored. For the next highest author, any papers coauthored with the first researcher were excluded, but credit was given for all other publications. This sequence was continued until we accounted for all researchers in a given department.

After compiling the databases, we examined the citation list for entries that were not journals (e.g., book chapters, presentations), and these entries were removed. Because these nonjournal entries were removed after exportation from Scopus, the total citations used in describing the cohort are likely to be greater than the final number used in all analyses performed using Bradford's law. The citation databases were constructed from December 2013 to January 2014.

### Bradford's Law

The quantitative relationship between zones relies on a sequence of ratios often described as $c:ck:ck^2$ for the

minimal 3-zone pattern, where c represents the number of journals in Zone 1 and k represents the Bradford multiplier. The parameter p represents the number of Bradford zones, which is generally accepted as ranging from a minimum of 3 to a maximum of 10.[26] The p parameter also sets the citation target for each zone, because the total number of citations (A) is equally divided into p zones. As an example, suppose there are 6 (c) core journals in a given area of research (Zone 1). If a researcher finds 15 articles of interest in those 6 journals in a month, but requires an additional 12 journals to find 15 more articles of interest (Zone 2), the Bradford multiplier would be 2 (k). For each subsequent 15 articles, a researcher would have to search 24 ($ck^2$) (Zone 3), then 48 ($ck^3$) (Zone 4), then 96 ($ck^4$) (Zone 5) journals, and so on. It is assumed that each field has its own c and k.

### Egghe's Formulation of Bradford's Law of Distribution

Bradford's law uses 3 parameters to model the $c:ck:ck^2 \ldots ck^{p-1}$ sequence using Egghe's formulation. Parameter c defines the core number of journals. Parameter k defines the Bradford multiplier. These parameters are dependent on the choice of p, which represents the number of zones. They can be solved using the equations below:

$$k = (e^{\gamma} Y_m)^{1/p} \quad \text{[Eq. 1]}$$

$$c = T(k - 1)/(k^p - 1) \quad \text{[Eq. 2]}$$

The 2 constants in Equation 1, e and γ, represent Euler's number and Euler's constant, respectively, where $e^{\gamma}$ = 1.781. $Y_m$ and T describe qualities of the database; $Y_m$ is the number of citations of the highest-ranked journal; and T is the cumulative number of journals in the database. Using these equations, a theoretical distribution of Bradford zones can be established for a citation database.

Egghe's formulation has been the most widely used derivation of Bradford's law for bibliometric analyses.[5] Using Egghe's formulation, one can create a graphical representation of Bradford's distribution. The following equations are used for this:

$$F(x) = a\log(1 + bx) \quad \text{[Eq. 3]}$$

$$a = (A/p)/\log k \quad \text{[Eq. 4]}$$

$$b = (k - 1)/c \quad \text{[Eq. 5]}$$

Each zone of journals should contain the same number of citations (A/p), where A is the total number of citations. Additionally, a separate analysis based on Bradford's verbal formulation was performed; the total number of citations was separated into p zones, and the number of journals in each zone was matched to the appropriate citation density. From these counts of journals, c was given as the count of journals from the first zone, and k was a common multiplier between zones.

### Subspecialty Analysis of Citation Density

Separate databases were created for each subspecialty. A cumulative database was also generated from the sum of the individual specialties to determine the core journals for all of neurosurgery. For surgeons who fell within multiple specialties, their citation counts were included for each specialty but were included only once when summing all specialties.

## Results

### Participating Academic Neurosurgeons and Cumulative Publication Database

The database was made up of 150 North American neurosurgeons representing 65 separate academic institutions. The median career h-index was 36. Over the 5-year period, the mean number of publications per author was 34 and the mean number of journal articles referenced per author was 1183. The mean number of references per publication per author was 37. These researchers also had an average self-citation rate of 1.33 per publication (Table 1).

This group of academic neurosurgeons authored 5095 articles in 671 unique journals from 2009 through 2013; these articles included 183,421 total journal article references. The top 10 journals that were most frequently published in were *Neurosurgery* (627 articles), *Journal of Neurosurgery* (391), *Neurosurgical Focus* (234), *World Neurosurgery* (225), *Journal of Neurosurgery: Spine* (189), *Journal of Neurosurgery: Pediatrics* (188), *Journal of Neuro-Oncology* (148), *Spine* (114), *Journal of Clinical Neuroscience* (105), and *Epilepsia* (84). These 10 journals represented 45% of the total publications (Table 2).

### Egghe's Formulation of Bradford's Law

The citation database was ranked in descending order of number of citations per journal (Table 3). The ranked citation density distribution can be seen in Fig. 2. The number of citations in the top journal, *Journal of Neurosurgery*, was used as $Y_m$ (13,577) and the total number of journals cited was used as T (7458). Using these values in the previously described Egghe's formulation, we solved for the theoretical citation distribution for 3 to 8 zones (p).

As previously observed in our application of Bradford's law, the citation distribution expected from Egghe's formulation again did not fit the observed citation distribution identified by our citation database (Fig. 3), because Egghe's formulation would predict that all zones carry an approximately equal distribution of citation density, but our distribution did not fit this expectation.[30] Therefore, Egghe's formulation was again abandoned for the verbal

**TABLE 1. Citation metrics for the top 150 neurosurgeons, ranked by h-index***

| Citation Metrics | Cumulative Results for Neurosurgery |
|---|---|
| h-Index | 36.9/36 (7–76) |
| Articles | 34/25 (1–148) |
| Citations in all articles | 1183/872 (19–8169) |
| Citations per publication | 37/28 (15.17–401) |
| Self-citations per paper | 1.33/0.97 (0–29) |

* Values reported as mean/median (range).

TABLE 2. The top 10 journals in which the top 150 academic neurosurgeons published from 2009 through 2013

| Rank | Journal | No. of Articles | Cumulative % of Total Articles |
|---|---|---|---|
| 1 | *Neurosurgery* | 627 | 12.31 |
| 2 | *Journal of Neurosurgery* | 391 | 19.98 |
| 3 | *Neurosurgical Focus* | 234 | 24.57 |
| 4 | *World Neurosurgery* | 225 | 28.99 |
| 5 | *Journal of Neurosurgery: Spine* | 189 | 32.70 |
| 6 | *Journal of Neurosurgery: Pediatrics* | 188 | 36.39 |
| 7 | *Journal of Neuro-Oncology* | 148 | 39.29 |
| 8 | *Spine* | 114 | 41.53 |
| 9 | *Journal of Clinical Neuroscience* | 105 | 43.59 |
| 10 | *Epilepsia* | 84 | 45.24 |

formulation of Bradford's law. A comparison of Bradford's verbal law with Egghe's formulation for combined neurosurgery and each subspecialty can be found in Table 4.

### Verbal Formulation of Bradford's Law

Using this method, we discovered that the distribution followed a pattern for certain values of p. Parameters c and k could be found for the first 3 zones that satisfy the verbal formulation, whereas all zones beyond 3 failed to reach the expected citation density for that Bradford multiplier. The closest fit across the first 3 zones was for p = 4 (Fig. 4). With this formula, the core journals of neurosurgery emerged as the top 8 ranked journals with a Bradford multiplier of 5. The core journals of neurosurgery ranked by citation are as follows: *Journal of Neurosurgery, Neurosurgery, Spine, Stroke, Neurology, American Journal of Neuroradiology, International Journal of Radiation Oncology Biology Physics*, and *New England Journal of Medicine*.

### Subspecialty Differences in Core Journals

A Bradford analysis was completed in a similar manner for each subspecialty (Table 5).

#### Neurosurgical Oncology

The mean self-citation rate was 0.93 citations/paper (range 0.34–2.13). The verbal formulation of Bradford's law for the neurosurgical oncology group demonstrated 5 journals within the core zone. The core journals as ranked by citation count are *Journal of Neurosurgery, Neurosurgery, International Journal of Radiation Oncology Biology Physics, Journal of Neuro-Oncology*, and *Journal of Clinical Oncology*.

#### Pediatrics

The mean self-citation rate was 1.28 citations/paper (range 0.11–2.89). As described previously,[30] the verbal formulation of Bradford's law for the pediatrics group demonstrated 9 journals within the core zone. The core journals as ranked by citation count are *Journal of Neurosurgery, Neurosurgery, Epilepsia, Child's Nervous System, Pediatric Neurosurgery, Neurology, Journal of Neuro-Oncology, Cancer Research*, and *New England Journal of Medicine*.

#### Peripheral Nerve

The mean self-citation rate was 0.84 citations/paper (range 0–6.17). The verbal formulation of Bradford's law for the peripheral nerve group demonstrated 10 journals within the core zone. The core journals as ranked by citation count are *Journal of Neurosurgery, Neurosurgery, Journal of Hand Surgery, Journal of Bone and Joint Surgery, Spine, Journal of Neuroscience, Experimental Neurology, Neurology, Biomaterials*, and *Plastic and Reconstructive Surgery*.

#### Skull Base

The mean self-citation rate was 2.59 citations/paper (range 0–29). The verbal formulation of Bradford's law for the skull base group demonstrated 6 journals within the core zone. The core journals as ranked by citation count are *Journal of Neurosurgery, Neurosurgery, Cancer Research, Surgical Neurology, Acta Neurochirurgica*, and *Journal of Neuro-Oncology.*

#### Spine

The mean self-citation rate was 0.84 citations/paper (range 0–2.24). The verbal formulation of Bradford's law for the spine group demonstrated 3 journals within the core zone. The core journals as ranked by citation count are *Spine, Journal of Neurosurgery*, and *Neurosurgery*.

#### Stereotactic and Functional

The mean self-citation rate was 1.18 citations/paper (range 0–3.88). The verbal formulation of Bradford's law for the stereotactic and functional group demonstrated 7 journals within the core zone. The core journals as ranked by citation count are *Journal of Neurosurgery, Neurosurgery, Epilepsia, Neurology, Journal of Neuroscience, Movement Disorders*, and *Brain*.

#### Vascular

The mean self-citation rate was 1.08 citations/paper (range 0.3–2.22). The verbal formulation of Bradford's law for the vascular group demonstrated 3 journals within the core zone. The core journals as ranked by citation count are *Stroke, Journal of Neurosurgery*, and *Neurosurgery*.

## Discussion

Bradford's law was used by Madhugiri et al. in 2013 to identify core journals for all of neurosurgery.[19] The aim of our current study was to further establish the use of Bradford's law in identifying core journals of neurosurgery by using a larger and more diverse sampling method while establishing the core journals for many neurosurgical subspecialties. Using the verbal formulation of Bradford's law, we found 8 journals in the core with a Bradford multiplier of 5. The core journals of neurosurgery ranked by citation are as follows: *Journal of Neurosurgery, Neurosurgery, Spine, Stroke, Neurology, American Journal of Neuroradiology, International Journal of Radiation*

**TABLE 3. The top 100 journals ranked by the number of times article citations occur within papers by the top 150 academic neurosurgeons from 2009 through 2013**

| Rank | Journal | No. of Times Cited | Cumulative % of Total Citations | Bradford's Theoretical % of Total Citations | Difference of Experimental vs Bradford Theoretical (%) |
|---|---|---|---|---|---|
| 1 | *Journal of Neurosurgery* | 13577 | 7.40 | 14.32 | 48.30 |
| 2 | *Neurosurgery* | 11983 | 13.94 | 19.94 | 30.12 |
| 3 | *Spine* | 5006 | 16.66 | 23.51 | 29.11 |
| 4 | *Stroke* | 4995 | 19.39 | 26.12 | 25.79 |
| 5 | *Neurology* | 2963 | 21.00 | 28.19 | 25.50 |
| 6 | *American Journal of Neuroradiology* | 2731 | 22.49 | 29.90 | 24.78 |
| 7 | *Int Journal of Radiation Oncology Biology Physics* | 2510 | 23.86 | 31.36 | 23.91 |
| 8 | *New England Journal of Medicine* | 2378 | 25.16 | 32.63 | 22.90 |
| 9 | *Acta Neurochirurgica* | 2185 | 26.35 | 33.76 | 21.95 |
| 10 | *Surgical Neurology* | 2122 | 27.51 | 34.77 | 20.89 |
| 11 | *Epilepsia* | 2107 | 28.65 | 35.68 | 19.70 |
| 12 | *Journal of Neuroscience* | 1830 | 29.65 | 36.52 | 18.82 |
| 13 | *Cancer Research* | 1809 | 30.64 | 37.30 | 17.86 |
| 14 | *Journal of Neuro-Oncology* | 1753 | 31.59 | 38.02 | 16.89 |
| 15 | *Journal of Clinical Oncology* | 1747 | 32.55 | 38.69 | 15.87 |
| 16 | *Neurosurgical Focus* | 1732 | 33.49 | 39.31 | 14.81 |
| 17 | *Proc of the Natl Academy of Sciences of the USA* | 1707 | 34.42 | 39.90 | 13.74 |
| 18 | *Cancer* | 1631 | 35.31 | 40.46 | 12.73 |
| 19 | *Child's Nervous System* | 1500 | 36.13 | 40.99 | 11.85 |
| 20 | *Nature* | 1421 | 36.90 | 41.49 | 11.05 |
| 21 | *Brain* | 1404 | 37.67 | 41.96 | 10.23 |
| 22 | *Journal of Neurology Neurosurgery and Psychiatry* | 1358 | 38.41 | 42.42 | 9.45 |
| 23 | *Science* | 1332 | 39.13 | 42.85 | 8.67 |
| 24 | *Lancet* | 1318 | 39.85 | 43.27 | 7.89 |
| 25 | *Annals of Neurology* | 1243 | 40.53 | 43.67 | 7.18 |
| 26 | *Radiology* | 1056 | 41.11 | 44.05 | 6.68 |
| 27 | *Journal of Neurotrauma* | 1041 | 41.67 | 44.42 | 6.18 |
| 28 | *Journal of Neurosurgery Spine* | 1009 | 42.22 | 44.78 | 5.70 |
| 29 | *Journal of the American Medical Association* | 1001 | 42.77 | 45.12 | 5.21 |
| 30 | *Clinical Cancer Research* | 882 | 43.25 | 45.45 | 4.84 |
| 31 | *Journal of Biological Chemistry* | 861 | 43.72 | 45.77 | 4.49 |
| 32 | *Brain Research* | 856 | 44.19 | 46.09 | 4.12 |
| 33 | *Journal of Cerebral Blood Flow and Metabolism* | 829 | 44.64 | 46.39 | 3.77 |
| 34 | *Pediatric Neurosurgery* | 826 | 45.09 | 46.68 | 3.41 |
| 35 | *Neuroimage* | 825 | 45.54 | 46.97 | 3.04 |
| 36 | *Neuroradiology* | 809 | 45.98 | 47.24 | 2.67 |
| 37 | *Journal of Neurophysiology* | 794 | 46.41 | 47.51 | 2.31 |
| 38 | *Neuro-Oncology* | 764 | 46.83 | 47.77 | 1.98 |
| 39 | *Movement Disorders* | 762 | 47.24 | 48.03 | 1.63 |
| 40 | *British Journal of Neurosurgery* | 699 | 47.63 | 48.28 | 1.35 |
| 41 | *Archives of Neurology* | 684 | 48.00 | 48.52 | 1.07 |
| 42 | *Laryngoscope* | 659 | 48.36 | 48.76 | 0.82 |
| 43 | *European Spine Journal* | 654 | 48.71 | 48.99 | 0.56 |
| 44 | *Journal of Clinical Endocrinology and Metabolism* | 649 | 49.07 | 49.21 | 0.30 |
| 45 | *Experimental Neurology* | 638 | 49.42 | 49.44 | 0.04 |

*(continued)*

**TABLE 3. The top 100 journals ranked by the number of times article citations occur within papers by the top 150 academic neurosurgeons from 2009 through 2013 *(continued)***

| Rank | Journal | No. of Times Cited | Cumulative % of Total Citations | Bradford's Theoretical % of Total Citations | Difference of Experimental vs Bradford Theoretical (%) |
|---|---|---|---|---|---|
| 46 | *Cell* | 636 | 49.76 | 49.65 | −0.22 |
| 47 | *Neurologia Medico Chirurgica* | 605 | 50.09 | 49.86 | −0.46 |
| 48 | *Stereotactic and Functional Neurosurgery* | 603 | 50.42 | 50.07 | −0.70 |
| 49 | *Acta Neurochirurgica Supplement* | 589 | 50.74 | 50.27 | −0.93 |
| 50 | *Journal of Clinical Neuroscience* | 588 | 51.06 | 50.47 | −1.17 |
| 51 | *Journal of Bone and Joint Surgery Series A* | 586 | 51.38 | 50.67 | −1.41 |
| 52 | *Critical Care Medicine* | 573 | 51.70 | 50.86 | −1.64 |
| 53 | *Acta Neuropathologica* | 560 | 52.00 | 51.05 | −1.87 |
| 54 | *Circulation* | 557 | 52.30 | 51.23 | −2.09 |
| 55 | *Oncogene* | 551 | 52.60 | 51.41 | −2.32 |
| 56 | *Neurosurgery Clinics of North America* | 539 | 52.90 | 51.59 | −2.54 |
| 57 | *Lancet Neurology* | 532 | 53.19 | 51.76 | −2.75 |
| 58 | *Neuron* | 503 | 53.46 | 51.94 | −2.94 |
| 59 | *Anesthesiology* | 482 | 53.73 | 52.10 | −3.11 |
| 60 | *Neuroscience* | 479 | 53.99 | 52.27 | −3.29 |
| 61 | *Journal of Neurosurgery Pediatrics* | 470 | 54.24 | 52.43 | −3.45 |
| 62 | *Neurological Research* | 468 | 54.50 | 52.59 | −3.62 |
| 63 | *Nature Medicine* | 463 | 54.75 | 52.75 | −3.79 |
| 64 | *Neurosurgical Review* | 460 | 55.00 | 52.91 | −3.96 |
| 65 | *Clinical Neurology and Neurosurgery* | 455 | 55.25 | 53.06 | −4.13 |
| 66 | *Clinical Orthopaedics and Related Research* | 452 | 55.50 | 53.21 | −4.30 |
| 67 | *Magnetic Resonance in Medicine* | 439 | 55.74 | 53.36 | −4.46 |
| 68 | *Journal of Neuropathology and Experimental Neurology* | 434 | 55.97 | 53.50 | −4.61 |
| 69 | *Minimally Invasive Neurosurgery* | 424 | 56.20 | 53.65 | −4.76 |
| 70 | *Journal of Vascular Surgery* | 419 | 56.43 | 53.79 | −4.91 |
| 71 | *American Journal of Roentgenology* | 418 | 56.66 | 53.93 | −5.06 |
| 72 | *Neurocritical Care* | 413 | 56.88 | 54.07 | −5.21 |
| 73 | *PLoS One* | 407 | 57.11 | 54.20 | −5.36 |
| 74 | *Journal of Immunology* | 406 | 57.33 | 54.34 | −5.50 |
| 75 | *Journal of Spinal Disorders and Techniques* | 403 | 57.55 | 54.47 | −5.65 |
| 76 | *Cancer Cell* | 379 | 57.75 | 54.60 | −5.78 |
| 77 | *Blood* | 359 | 57.95 | 54.73 | −5.88 |
| 78 | *Clinical Neurosurgery* | 348 | 58.14 | 54.86 | −5.98 |
| 79 | *Epilepsy Research* | 346 | 58.33 | 54.98 | −6.08 |
| 80 | *Nature Genetics* | 345 | 58.52 | 55.11 | −6.19 |
| 81 | *Journal of Trauma Injury Infection and Critical Care* | 341 | 58.70 | 55.23 | −6.29 |
| 82 | *Journal of Comparative Neurology* | 336 | 58.89 | 55.35 | −6.39 |
| 83 | *Journal of Neurochemistry* | 334 | 59.07 | 55.47 | −6.48 |
| 84 | *Clinical Neurophysiology* | 331 | 59.25 | 55.59 | −6.58 |
| 85 | *International Journal of Cancer* | 326 | 59.43 | 55.71 | −6.68 |
| 86 | *Otolaryngology Head and Neck Surgery* | 325 | 59.60 | 55.82 | −6.78 |
| 87 | *British Journal of Cancer* | 321 | 59.78 | 55.93 | −6.87 |
| 88 | *Nature Neuroscience* | 316 | 59.95 | 56.05 | −6.96 |
| 89 | *Annals of Surgery* | 308 | 60.12 | 56.16 | −7.05 |
| 90 | *Journal of Spinal Disorders* | 303 | 60.28 | 56.27 | −7.13 |

*(continued)*

**TABLE 3. The top 100 journals ranked by the number of times article citations occur within papers by the top 150 academic neurosurgeons from 2009 through 2013 *(continued)***

| Rank | Journal | No. of Times Cited | Cumulative % of Total Citations | Bradford's Theoretical % of Total Citations | Difference of Experimental vs Bradford Theoretical (%) |
|---|---|---|---|---|---|
| 91 | *Journal of Neuroscience Research* | 299 | 60.45 | 56.38 | −7.21 |
| 92 | *Journal of the National Cancer Institute* | 298 | 60.61 | 56.49 | −7.30 |
| 93 | *Cerebral Cortex* | 296 | 60.77 | 56.59 | −7.38 |
| 94 | *Journal of Magnetic Resonance Imaging* | 292 | 60.93 | 56.70 | −7.46 |
| 95 | *Cerebrovascular Diseases* | 290 | 61.09 | 56.80 | −7.54 |
| 96 | *Canadian Journal of Neurological Sciences* | 285 | 61.24 | 56.91 | −7.62 |
| 97 | *Molecular Therapy* | 282 | 61.40 | 57.01 | −7.70 |
| 98 | *American Journal of Pathology* | 279 | 61.55 | 57.11 | −7.77 |
| 99 | *British Medical Journal* | 276 | 61.70 | 57.21 | −7.84 |
| 100 | *Journal of Clinical Investigation* | 275 | 61.85 | 57.31 | −7.92 |

*Oncology Biology Physics*, and *New England Journal of Medicine*.

Many mathematical approaches exist that apply Bradford's law of scattering to data sets.[4,5,18,26] This study uses Egghe's expansion of Leimkuhler's method, which has been used in other studies.[5,18,19,26] This formulation relies on the use of exponential functions to predict zonal distribution and depends on the citation database parameters of total citations by the top journal and the total number of journals; however, no mathematical formulation has achieved consistent statistical significance.[9] Additionally, how does this type of analysis compare with the more traditional journal ranking that uses the IF? Journal IF is defined as the average number of citations per paper from the prior 2 years of publication. This value is relevant for journals to compare their impact to that of other journals within equivalent fields of study. It is not useful for comparing journals across subjects due to the scope of readership differences. For example, *Journal of Neurosurgery* and *New England Journal of Medicine* were both found to be core journals for neurosurgery, but their IFs are quite different (3.227 vs 54.42, respectively [2013 IF]). The value of a Bradford's law analysis is that it attempts to analyze utility to a given topic or field regardless of relative overall impact, and is inclusive of journals across traditional field barriers.

Practical application of Bradford's law in neurosurgery may best be applied to neurosurgical subspecialties. Many neurosurgeons have completed fellowships resulting in specialized practices and research interests. An analysis targeted to the major subspecialties would yield more focused and practical results. Additionally, identifying these core journals in neurosurgical subspecialties may also guide medical students, residents, and fellows to the journals that will have the highest impact within their field of interest.

Our sampling method differs from that of Madhugiri et al.[19] in that rather than sampling articles in neurosurgery-specific journals (22,850 citations over a 3-month period), we chose to sample all publications from the top 25 neurosurgeons as ranked by h-index for each chosen subspecial-

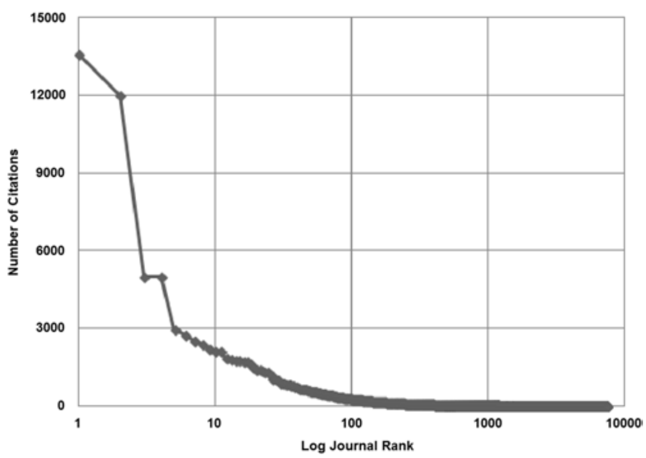


**FIG. 2.** Citation counts for cumulative database of neurosurgery journals.

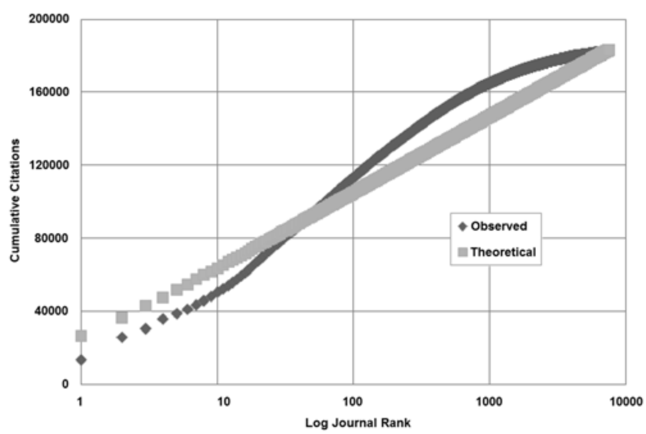


**FIG. 3.** Graphical comparison of observed data versus Bradford's graphical law for cumulative database of neurosurgery journals.

**TABLE 4. Comparison of 4-zone distribution of Bradford's verbal formulation versus Egghe's theoretical for all of neurosurgery and its subspecialties**

| | | Bradford's Verbal Formulation | | | Egghe's Formulation | | |
|---|---|---|---|---|---|---|---|
| Subspecialty | Zone | Journals | Citations | % Difference from Theoretical* | Journals | Citations | % Difference from Theoretical* |
| Combined† | 1 | 8 | 46143 | 0.63 | 4 | 35561 | −22.45 |
| | 2 | 39 | 45738 | −0.26 | 44 | 56923 | 24.14 |
| | 3 | 211 | 45892 | 0.08 | 550 | 63959 | 39.48 |
| | 4 | 7200 | 45648 | −0.45 | 6860 | 26978 | −41.17 |
| Neurosurgical oncology | 1 | 5 | 8016 | −2.41 | 4 | 7256 | −7.30 |
| | 2 | 27 | 7919 | −1.17 | 29 | 8824 | 12.73 |
| | 3 | 141 | 7828 | −0.01 | 242 | 9608 | 22.75 |
| | 4 | 2123 | 7546 | 3.59 | 2021 | 5621 | −28.19 |
| Pediatrics | 1 | 9 | 6053 | −1.73 | 5 | 4490 | −24.54 |
| | 2 | 36 | 5928 | 0.37 | 37 | 7200 | 21.01 |
| | 3 | 160 | 5944 | 0.10 | 265 | 7557 | 27.01 |
| | 4 | 2026 | 5873 | 1.29 | 1924 | 4551 | −23.51 |
| Peripheral nerve | 1 | 10 | 1836 | 2.22 | 9 | 1745 | −7.07 |
| | 2 | 44 | 1884 | −0.33 | 43 | 1927 | 2.62 |
| | 3 | 172 | 1877 | 0.04 | 219 | 2147 | 14.34 |
| | 4 | 1151 | 1914 | −1.93 | 1106 | 1692 | −9.89 |
| Skull base | 1 | 6 | 5996 | −1.46 | 4 | 5269 | −10.84 |
| | 2 | 32 | 5905 | 0.08 | 31 | 6348 | 7.42 |
| | 3 | 163 | 5912 | −0.04 | 246 | 7257 | 22.80 |
| | 4 | 2042 | 5825 | 1.43 | 1963 | 4764 | −19.38 |
| Spine | 1 | 3 | 6714 | 1.49 | 3 | 6714 | −1.49 |
| | 2 | 43 | 6875 | −0.87 | 31 | 7339 | 7.68 |
| | 3 | 215 | 6809 | 0.10 | 280 | 7937 | 16.45 |
| | 4 | 1995 | 6865 | −0.72 | 2552 | 5273 | −22.64 |
| Stereotactic & functional | 1 | 7 | 7108 | 2.09 | 6 | 6449 | −11.17 |
| | 2 | 29 | 7240 | 0.27 | 42 | 9306 | 28.19 |
| | 3 | 125 | 7262 | −0.03 | 303 | 8642 | 19.04 |
| | 4 | 2359 | 7429 | −2.33 | 2169 | 4642 | −36.06 |
| Vascular | 1 | 3 | 11489 | 12.23 | 3 | 11489 | 12.23 |
| | 2 | 22 | 10277 | 0.39 | 27 | 11119 | 8.62 |
| | 3 | 148 | 10234 | −0.03 | 251 | 11594 | 13.26 |
| | 4 | 2084 | 8593 | −16.06 | 2332 | 6746 | −34.10 |

* Percent difference compares each formulation's value against the theoretical value.
† In a 4-zone model ($p = 4$), the citation count per zone theoretically should be 45,855.

ty (183,421 citations over a 5-year period from 150 neurosurgeons). These subspecialty databases were combined to evaluate neurosurgery as a whole. These parameters were chosen to construct a database large enough from which to draw meaningful conclusions, yet not broad enough to make data collection and analysis prohibitively labor intensive. Although seemingly arbitrary, any analysis of this type must adhere to specific parameters, because full and detailed sampling of all the neurosurgical literature is simply not possible. This type of sampling technique is not novel to Bradford's law analyses.[9,26] We chose to sample the citations of highly cited neurosurgeons because it would capture those articles that neurosurgeons cite in journals that—although unconventional to neurosurgery—may be high-impact articles and relevant to their respective subspecialty.

Productivity, in the sense of citation or publication count, is not a guarantee of quality. The h-index does attempt to quantify and measure quality in terms of productivity. An author must continue to publish papers over time (productivity) and have his or her papers cited by peers over time (loosely correlated with quality or, more appropriately, relevance). A citation has been equated to a measure of trust between one author and another regarding the quality of the work.[2] Therefore, those neurosurgeons who are in the top 25 for each subspecialty as ranked by h-index are presumably currently publishing and citing relevant works in their subspecialty.[11,14]

The citation distributions for neurosurgery and its subspecialties did not fit the expected distributions based on currently accepted formulations of Bradford's law. This is an issue common to many other researchers and consistent with previous Bradford's law studies in neurosurgery.[10,19,26,30] The observed distribution showed a greater number of citations in the central zones than expected, while the first and last zones contained fewer citations. This difference was consistent across subspecialties, although it was most exaggerated for pediatrics, in which the observed distribution was furthest from the model. Neurosurgery as a whole is a broad field encompassing most of the other subspecialties. Not surprisingly then, Egghe's expected distribution as applied to neurosurgery as a whole most resembles the pediatrics distribution.

It has recently been suggested that highly interdisciplinary fields will produce a Bradford distribution with increased scatter, or similar to the distribution previously discussed. When a subject or field is highly interdisciplinary, the distribution of the information relevant to that field or subject will be scattered across a greater number of journals, diminishing the strength of the core journals while inflating the secondary zones. The highly interdisciplinary nature of neurosurgery may account for the distribution observed within neurosurgical literature.[9] The concept of interdisciplinarity and its impact on the production of scientific literature has only recently been described by Hjørland.[9,10,21] Continued research on interdisciplinarity and its impact on the distribution of scientific literature is needed.

The differences in the distribution of the observed data and the expected model distribution may also be explained by the journals that make up each zone. The core zones for each subspecialty of neurosurgery are all different, but *Journal of Neurosurgery* and *Neurosurgery* are represented in the core of all neurosurgical specialties, ranking as the first and second journal, respectively, for all subspecialties except spine and vascular, for which they are second and third. These journals represent the most specific and inclusive journals of neurosurgery. The central zones contain some journals that, although less specific, traditionally have a higher impact with a much broader scope. These journals represent a smaller number of articles, but by virtue of the IF of these journals, they may be highly impactful. An analysis of the impact a specific research article has on a journal or zone was beyond the scope of this study.

How does this work affect the average neurosurgeon? The rapid expansion of scientific literature is likely to continue, making it even more difficult for general and subspecialty neurosurgeons to keep abreast of all pertinent research being published monthly or quarterly. We have shown that many journals with broader readership or that traditionally are nonneurosurgical, like *New England Journal of Medicine*, are publishing highly cited works that are having an impact within our field. Kondziolka responded to the article by Madhugiri et al. in which he calls into question the current structure of the flow of knowledge (i.e., article submission/peer review/publication/citation) as "fundamentally flawed."[16] There are many other avenues that clinician researchers can use to stay up to date on current research. These include conferences, advanced courses, journal clubs, teaching sessions for residents and

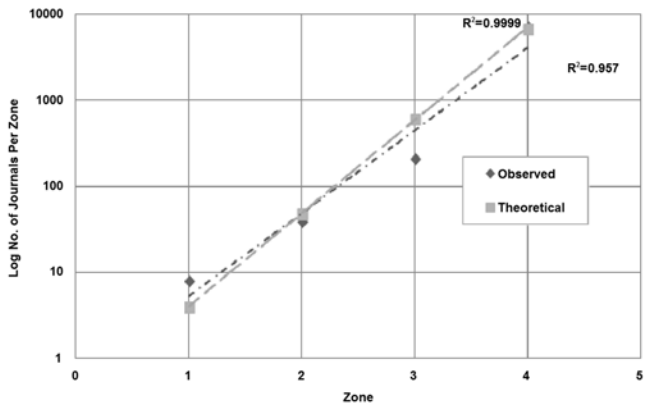


**FIG. 4.** Zonal citation distribution of Bradford's verbal formulation versus observed.

fellows, electronic resources, and even our patients themselves. This paper serves to identify the core journals in the various neurosurgical subspecialties based on the academic productivity of the top-producing North American neurosurgeons. By identifying the core journals for each neurosurgical subspecialty, we believe readership can be directed to those journals most likely to have a consistently high impact while not overlooking those journals that may be traditionally nonneurosurgical but that may contain a smaller number of especially high-impact articles.

## Limitations

This study can only be as accurate as the database used to complete it (i.e., Scopus). Scopus may have multiple entries for some researchers based on variations in name reporting. These entries generally included few or singular publications that may or may not have met our inclusion criteria and were not included in this analysis. With such a large sample size (183,421 citations), we considered the lack of these entries to be negligible. The export utility in Scopus is limited to 160 rows of data, and thus, the inclusion criteria were broken into smaller partitions to accommodate this limitation; however, when viewing all citations used by an author, Scopus eliminates duplicate references, and by exporting smaller partitions of the whole, some of these duplications may have been included.

Although Bradford's law was originally intended to be used for complete databases,[3] the rapid expansion of scientific literature makes the application to broad topics, such as neurosurgery, impractical.[28] However, by limiting the amount of literature sampled, the possibility of introducing selection bias exists. One such bias may be regional preference of journals from which authors choose to cite. We previously analyzed the potential for such bias within pediatric neurosurgery.[30] When comparing journal preferences for citations based on region, we found that although the top journal differed between North American and European pediatric neurosurgeons, there was considerable homogeneity when looking at the core journals from each group. Therefore, this study represents the core journals for North American neurosurgery, but probably has impact for practitioners in other regions. Additionally, senior

**TABLE 5. Cumulative and subspecialty-specific core journals***

| Rank | Combined | Subspecialty: Neurosurgical Oncology | Pediatrics | Peripheral Nerve | Skull Base | Spine | Stereotactic & Functional | Vascular |
|---|---|---|---|---|---|---|---|---|
| 1 | *Journal of Neurosurgery* | *Journal of Neurosurgery* | *Journal of Neurosurgery* | *Journal of Neurosurgery* | *Journal of Neurosurgery* | *Spine* | *Journal of Neurosurgery* | *Stroke* |
| 2 | *Neurosurgery* | *Neurosurgery* | *Neurosurgery* | *Neurosurgery* | *Neurosurgery* | *Journal of Neurosurgery* | *Neurosurgery* | *Journal of Neurosurgery* |
| 3 | *Spine* | *Int Journal of Radiation Oncology Biology Physics* | *Epilepsia* | *Journal of Hand Surgery* | *Cancer Research* | *Neurosurgery* | *Epilepsia* | *Neurosurgery* |
| 4 | *Stroke* | *Journal of Neuro-Oncology* | *Child's Nervous System* | *Journal of Bone and Joint Surgery* | *Surgical Neurology* | — | *Neurology* | — |
| 5 | *Neurology* | *Journal of Clinical Oncology* | *Pediatric Neurosurgery* | *Spine* | *Acta Neurochirurgica* | — | *Journal of Neuroscience* | — |
| 6 | *American Journal of Neuroradiology* | — | *Neurology* | *Journal of Neuroscience* | *Journal of Neuro-Oncology* | — | *Movement Disorders* | — |
| 7 | *Int Journal of Radiation Oncology Biology Physics* | — | *Journal of Neuro-Oncology* | *Experimental Neurology* | — | — | *Brain* | — |
| 8 | *New England Journal of Medicine* | — | *Cancer Research* | *Neurology* | — | — | — | — |
| 9 | — | — | *New England Journal of Medicine* | *Biomaterials* | — | — | — | — |
| 10 | — | — | — | *Plastic and Reconstructive Surgery* | — | — | — | — |

* Dashes represent a space where no journal is present; each subspecialty has a different number of core journals.

researchers may have preferences for which journals they choose to cite (i.e., more established journals with higher IFs vs newer, open access journals), which may influence the results of this analysis. More studies are needed to analyze citation preference between various academic ranks. Finally, this study may be limited by self-citation, as with any study of citation (h-index, journal IF, and so on). The mean and range of self-citation rates for the top 25 academic neurosurgeons in each subspecialty are reported.

## Conclusions

Bradford's law of distribution has been underapplied to fields of academic medicine. We present the first core journal analysis for neurosurgical subspecialties and an expanded look at the core journals for all of neurosurgery. Although each subspecialty has its own unique core of journals, *Journal of Neurosurgery* and *Neurosurgery* are among the core journals for all subspecialties. We propose that the current core journals for neurosurgery ranked by citation are as follows: *Journal of Neurosurgery, Neurosurgery, Spine, Stroke, Neurology, American Journal of Neuroradiology, International Journal of Radiation Oncology Biology Physics*, and *New England Journal of Medicine*.

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## Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

## Author Contributions

Conception and design: Klimo, Venable, Shepherd. Acquisition of data: all authors. Analysis and interpretation of data: Klimo, Venable, Shepherd. Drafting the article: Klimo, Venable, Shepherd. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Klimo. Statistical analysis: Venable, Shepherd. Study supervision: Klimo.

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