Original Article

The top 2,000 cited articles in critical care medicine: a bibliometric analysis

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Background: The bibliometric analysis has been performed on several topics in critical care medicine (CCM) focusing on top 100 cited articles, but the analysis on CCM literature as a whole is missing. The present study aimed to perform a complete bibliometric analysis in the field of CCM.

Methods: An electronic search of the Scopus database was performed on Feb 13, 2018. The search strategy involved core terms related to CCM. The top 2,000 most cited articles in the field of CCM were included in the analysis. Descriptive statistics on these top-cited articles, country distributions, and journals are reported. Individual author's productivity was assessed with the Lotka's law. Co-occurrence of keywords was visualized with the Fruchterman-Reingold layout. The Walktrap algorithm was employed for clustering analysis.

Results: A total of 2,000 documents were included in the analysis with median citations of 386 times [interquartile range (IQR): 308–562 times]. The most cited article was the original paper that described the Acute Physiology and Chronic Health Evaluation (APACHE) II score. The included articles were published in 411 journals. The median number of documents published in one journal was 1, and the mean number was 4.9, indicating a skewed distribution. The maximum number of publications was 217 in CCM. Author's productivity profile was significantly different from the Lotka's law (P=0.001), with n and C values of 2.8 and 0.52, respectively. Fruchterman-Reingold network plot showed that studies involving human subject were the most common literature type. Sepsis was a major research topic that co-occurred with keywords such as disease severity, nonhuman, risk assessment and practice guideline.

Conclusions: The study performed bibliometric analyses of 2,000 top-cited articles in CCM. The most cited article was the one which developed the APACHE II score. Author's productivity was significantly different from the Lotka's law.

Keywords: Bibliometric; critical care; sepsis; Lotka's law; Fruchterman-Reingold layout; top cited

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Introduction

Critical care medicine (CCM) is becoming increasingly important in a society with aging population. Elderly patients typically have multiple comorbidities and an acute illness such as pneumonia, myocardial infarction, or sepsis that may cause acute decompensation or a new critical illness requiring intensive care unit (ICU) admission (1,2). For example, myocardial infarction could cause cardiogenic shock and acute hypoxic respiratory failure (3). These critically ill patients with multiple comorbidities are at increased risk of in-hospital morbidity and mortality. Furthermore, CCM plays an essential role in the management of bird flu influenza pandemics, injuries caused by motor vehicle collisions, septic shock and natural disasters (4,5). Therefore, CCM is receiving greater attentions from researchers and healthcare professionals. Increasing awareness of the importance of CCM is reflected by the expanding number of publications within this specialty, including pre-clinical and translational clinical practice research studies. The bibliometric studies can help to (I) identify hotspots in a certain area; (II) network connections between subspecialties; (III) the leading investigators; and (IV) author's scientific output. Many bibliometric studies focused on a few vital issues in the field of CCM such as sepsis, severe brain injury and acute kidney injury (6-8). However, to the best of our knowledge, there is no bibliometric study that analyzes the entire CCM area. In this study, we performed a bibliometric analysis of the 2,000 most cited articles in the specialty of CCM, while aiming to provide an overview of CCM research and reveal connections among them.

Methods

Search strategy and study selection

An electronic search of the Scopus database was performed on Feb 13, 2018. The search strategy involved core terms related to CCM and the specific search strategy was as follows: (TITLE-ABS-KEY (critical AND care) OR TITLE-ABS-KEY (intensive AND care) OR TITLE-ABS-KEY (critically AND ill) AND SRCTYPE (j). There was no language restriction.

The number of citations was used as one of the criteria for the selection of studies, to ensure that the included documents were representative of the most influential articles in the field of CCM. The top 2,000 most cited articles were included in the final analysis.

Epidemiological description of included documents

The top ten most cited articles were retrieved, along with their journals and the year of publication. The leading contributors in CCM was also reported. A histogram ranking of the contributors by the number of highly cited documents was depicted. A pie chart was used to examine the distribution of highly cited documents by countries.

Lotka's law

The Lotka's law was employed to explore the frequency of publication by authors in CCM (9). The number of authors making x contributions is a fraction of the number making a single contribution, following the formula $1/x^n$ where n nearly always equals two, which is an approximation of the inverse-square law. The number of authors publishing a certain number of articles is a fixed ratio to the number of authors publishing a single article. As the number of published articles increases, authors producing that many publications become less frequent. The general form is described by the following equation:

$$X^n Y=C$$

where X is the number of publications, Y is the relative frequency of authors with X publications, and n and C are constants depending on the specific field. The aim of the analysis was to find the constants for n and C. The Pao's table was employed to display descriptive statistics of publications and authors (10).

Co-occurrence network

A keywords co-occurrence network was generated with the Fruchterman-Reingold layout, which is a force-directed graph drawing algorithm to create a visual object (11). Keywords with the 30 highest frequencies were displayed in the network plot. Clustering analysis was conducted with the Walktrap algorithm, a method based on the idea that random walks throughout the graph tend to detect subgraphs (areas of the graph with high edge density) as there are only few links that lead outside a given community (12).

Clustering analysis for keywords

A heat map was drawn for the clustering analysis (13). As the keywords constitute a binary matrix, the vectors are regarded as binary bits, and non-zero elements were "on"

Table 1 The top ten most cited articles in the field of critical care medicine

Title	Year	Journal	Citations
APACHE II: A severity of disease classification system	1985	*Critical Care Medicine*	10,167
Intensive insulin therapy in critically ill patients	2001	*New England Journal of Medicine*	7,050
Early goal-directed therapy in the treatment of severe sepsis and septic shock	2001	*New England Journal of Medicine*	6,332
Definitions for sepsis and organ failure and guidelines for the use of innovative therapies in sepsis	1992	*Chest*	5,518
Epidemiology of severe sepsis in the United States: Analysis of incidence, outcome, and associated costs of care	2001	*Critical Care Medicine*	5,120
American College of Chest Physicians/Society of Critical Care Medicine Consensus Conference: definitions for sepsis and organ failure and guidelines for the use of innovative therapies in sepsis	1992	*Critical Care Medicine*	4,134
A New Simplified Acute Physiology Score (SAPS II) Based on a European/North American Multicenter Study	1993	*JAMA: The Journal of the American Medical Association*	4,050
The SOFA (Sepsis-related Organ Failure Assessment) score to describe organ dysfunction/failure	1996	*Intensive Care Medicine*	3,966
Surviving sepsis campaign: International guidelines for management of severe sepsis and septic shock: 2008	2008	*Critical Care Medicine*	3,446
Acute renal failure - definition, outcome measures, animal models, fluid therapy and information technology needs: the Second International Consensus Conference of the Acute Dialysis Quality Initiative (ADQI) Group	2004	*Critical Care (London, England)*	3,346

and zero elements were "off". The distance is defined as the proportion of bits in which only one is "on" amongst those with at least one is "on". The Ward's minimum variance method was employed for hierarchical clustering analysis, aiming at finding compact, spherical clusters (14).

Results

The top ten most cited documents in the field of CCM

A total of 2,000 articles were included in the analysis. These articles were cited by a median of 386 times [interquartile range (IQR): 308–562 times]. The top ten most cited articles are shown in *Table 1*. Four papers were published in *Critical Care Medicine*, two in the *New England journal of medicine* (*NEJM*), one each in the *Journal of Medical Association of America* (*JAMA*), *Intensive Care Medicine*, *Critical Care* and *Chest*. The most cited article was published in 1985 in *Critical Care Medicine* by Knaus *et al*. that described the APACHE II score (15,16). The score is widely used in clinical practice, as well as in clinical research as a benchmark index of illness severity. The second and third most cited articles were original articles focused on the management of hyperglycemia and early goal directed therapy (EGDT), in the critically ill patients, respectively (16,17). While the former topic is a commonly encountered condition in the ICU, the latter is one of the hottest topics of research in critical care in recent years. Four of the ten documents focused on sepsis (16,18-20), three described scoring systems for risk stratification of critically ill patients (15,21,22), and four were clinical practice guidelines or consensus (18-20,23).

Source journals

The included 2,000 articles were published in 411 journals. The median number of documents published in one journal was 1, and the mean number was 4.9, indicating a skewed distribution. The maximum number of publications was 217 in *Critical Care Medicine* journal. The nine important journals were *NEJM*, *JAMA*, *Critical Care Medicine*, *Critical Care*, *Intensive Care Medicine*, *Pediatrics*, *British Medical Journal* (*BMJ*), *the Lancet* and *Chest* (*Figure 1*). The number

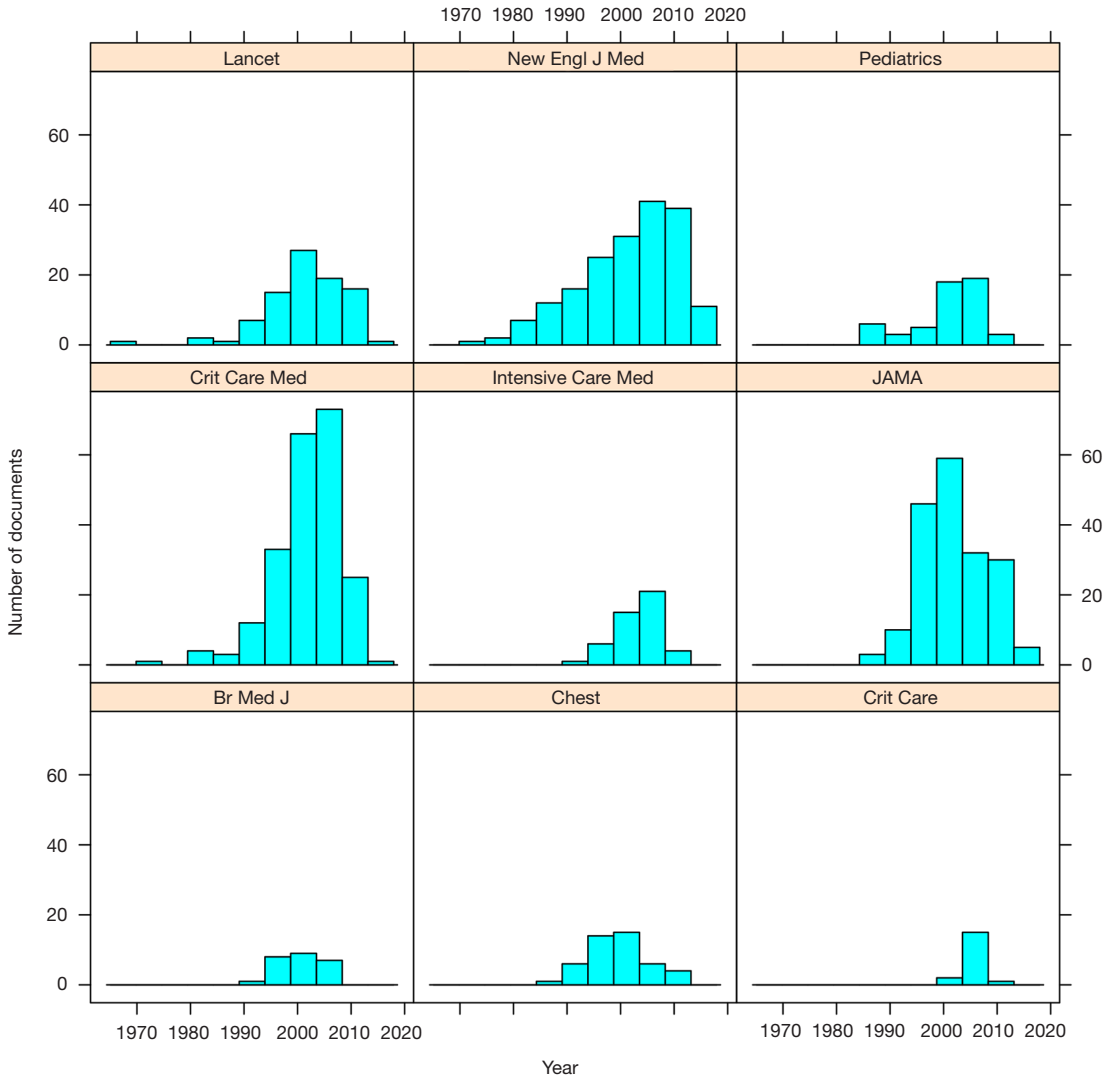

Figure 1 Number of highly cited articles published in major journals across years. The top nine important journals for the publication of highly-cited critical care literature were *NEJM*, *JAMA*, *Critical Care Medicine*, *Critical Care*, *Intensive Care Medicine*, *Pediatrics*, *British Medical Journal* (*BMJ*), the *Lancet* and *Chest*.

of highly cited articles published in these nine journals generally followed a normal distribution across years. The number of publications in *the Lancet* increased initially, with a peak in the year of 2,000, and then went down.

Leading contributors of the highly cited articles

Of the 2,000 highly cited articles, Bellomo R contributed the most [30], followed by Vincent JL [29], Bernard GR [21], Angus DC [17], and Reinhart K [17] (*Figure 2*). The United State of America contributed more than half (50.7%) of the highly cited articles, followed by Canada (8.4%), France (7.2%), Germany (4.3%), Australia (3.4%), Spain (3.2%), Italy (3.0%), Netherlands (2.4%), Belgium (2.2%), Switzerland (1.8%), Sweden (1.4%) and China (1.0%), as shown in *Figure 3*.

The Lotka's law was employed to explore the frequency of the publications by the authors in the field of CCM (*Table 2*). The beta coefficient was 2.8 (P=0.001 for two-sample Kolmogorov-Smirnov test between the empirical and the theoretical Lotka's law distribution with Beta =2) and the constant C was 0.52. The goodness of fit of the

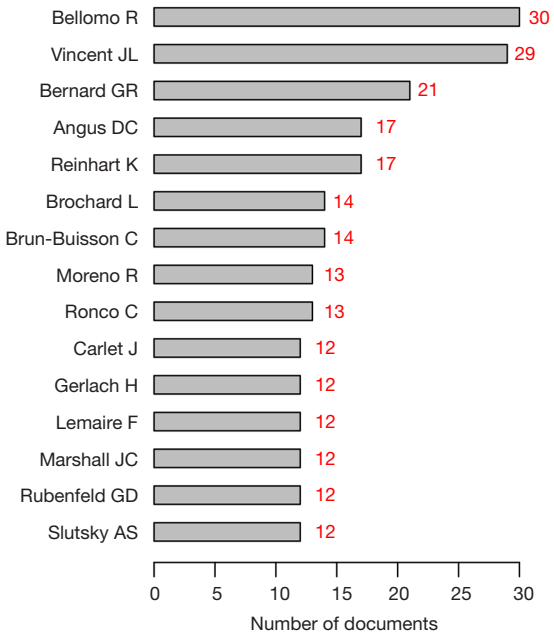

Figure 2 Leading contributors of highly cited articles. Of the 2,000 highly cited articles, Bellomo R contributed the most [30], followed by Vincent JL [29], Bernard GR [21], Angus DC [17], and Reinhart K [17].

empirically fitted model was optimal, as represented by the R-square value of 0.96. The meaning of the result is that authors making 2, 3 and 4 documents can be estimated with $\frac{1}{2^{2.8}}\times12,872=1,848$, $\frac{1}{3^{2.8}}\times12,872=549$ and $\frac{1}{4^{2.8}}\times12,872=265$, respectively. The constant C was described in the method section that the number of authors making 1 documents accounted for 0.52 of the total number of authors.

Text mining of index keywords

A total of 1,919 keywords were identified in the 2,000 analyzed documents. These keywords appeared in the articles for a median of 40 times (IQR: 27–56 times). The occurrence of the keywords in the cumulative number of articles by year is shown in *Figure 4*. Keywords such as human, female, male, humans, priority journal and articles appeared most frequently in CCM literature. *Figure 5* shows the co-occurrence of these keywords with the Fruchterman-Reingold layout. The size of the nodes represents the frequency of occurrence. The edges between the nodes indicate their co-occurrence in the same article. Studies involving human subject were the most common literature

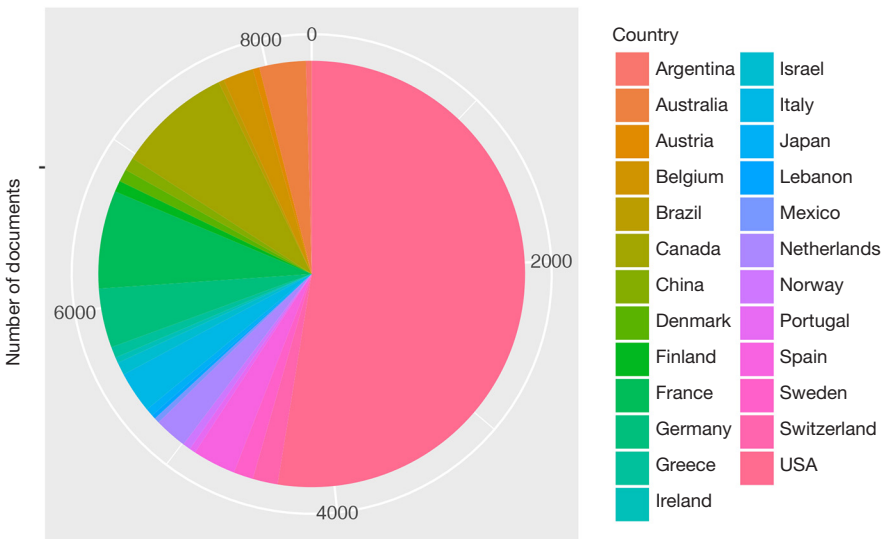

Figure 3 Number of articles across countries. The United States contributed more than half (50.7%) of the highly cited articles, followed by Canada (8.4%), France (7.2%), Germany (4.3%), Australia (3.4%), Spain (3.2%), Italy (3.0%), Netherlands (2.4%), Belgium (2.2%), Switzerland (1.8%), Sweden (1.4%) and China (1.0%).

Table 2 Calculation of n for the first 23 points using Pao's suggested table

No. of points	No. of articles (x)	No. of authors (y)	Frequency	X = logx	Y = logy	XY	XX
1	1	12,872	0.84490	0.0000000	9.4628097	0.000000	0.000
2	2	1,523	0.09997	0.6931472	7.3284374	5.079686	0.480
3	3	414	0.02717	1.0986123	6.0258660	6.620090	1.207
4	4	168	0.01103	1.3862944	5.1239640	7.103322	1.922
5	5	78	0.00512	1.6094379	4.3567088	7.011852	2.590
6	6	67	0.00440	1.7917595	4.2046926	7.533798	3.210
7	7	30	0.00197	1.9459101	3.4011974	6.618425	3.787
8	8	18	0.00118	2.0794415	2.8903718	6.010359	4.324
9	9	14	0.00092	2.1972246	2.6390573	5.798602	4.828
10	10	10	0.00066	2.3025851	2.3025851	5.301898	5.302
11	11	8	0.00053	2.3978953	2.0794415	4.986283	5.750
12	12	6	0.00039	2.4849066	1.7917595	4.452355	6.175
13	13	6	0.00039	2.5649494	1.7917595	4.595772	6.579
14	14	5	0.00033	2.6390573	1.6094379	4.247399	6.965
15	15	6	0.00039	2.7080502	1.7917595	4.852175	7.334
16	16	2	0.00013	2.7725887	0.6931472	1.921812	7.687
17	17	1	0.00007	2.8332133	0.0000000	0.000000	8.027
18	19	1	0.00007	2.9444390	0.0000000	0.000000	8.670
19	21	1	0.00007	3.0445224	0.0000000	0.000000	9.269
20	22	2	0.00013	3.0910425	0.6931472	2.142547	9.555
21	23	1	0.00007	3.1354942	0.0000000	0.000000	9.831
22	36	1	0.00007	3.5835189	0.0000000	0.000000	12.842
23	38	1	0.00007	3.6375862	0.0000000	0.000000	13.232

type. Sepsis was a major research topic that co-occurred with keywords such as disease severity, nonhuman, risk assessment and practice guidelines. The Walktrap algorithm identified two clusters for the keywords pool. The two clusters were represented by blue and yellow colors in the nodes, and also by the shaded area. The blue cluster involves clinical trials investigating effective of a treatment on clinical outcomes. The yellow cluster involves studies investigating risk factors or disease severity (*Figure 5*).

Clustering analysis for keywords

Several clusters can be identified from *Figure 6*. There was a cluster involving the studies of diabetes mellitus and cardiovascular diseases in CCM. Another cluster is related to the clinical trials investigating risk factors of mortality outcome. However, sepsis and septic shock constituted a small cluster.

A word cloud graph (*Figure 7*) was created by excluding general terms such as human, female, male, priority journal, humans, article, adult and age. The word cloud shows the frequency of occurrence of a keyword. Keywords such as "intensive care unit", "mortality", "critical illness" and "length of stay" were the most commonly occurring.

Discussion

Our study included 2,000 most cited articles in the field

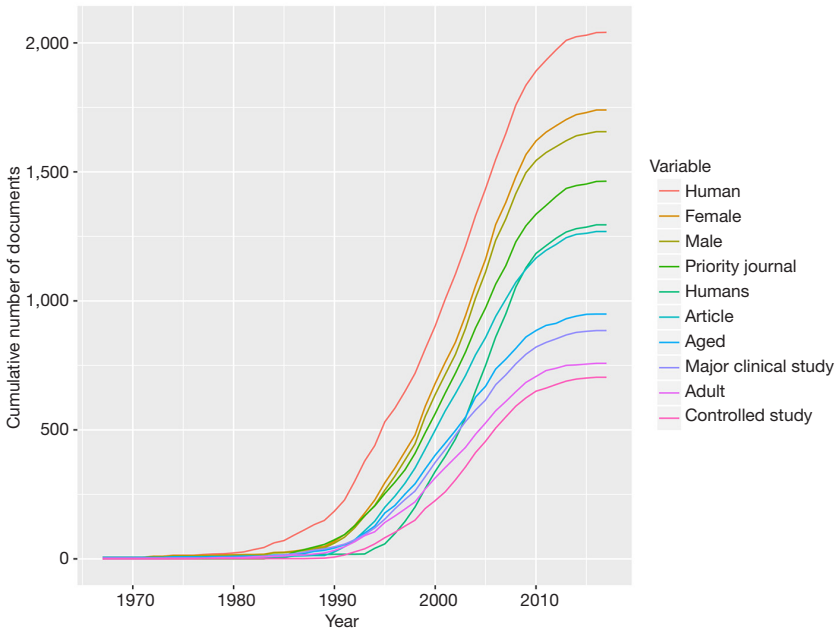

Figure 4 The occurrence of keywords in cumulative number of articles by year. It showed that keywords such as human, female, male, humans, priority journal and articles appeared most frequently in CCM literature. CCM, critical care medicine.

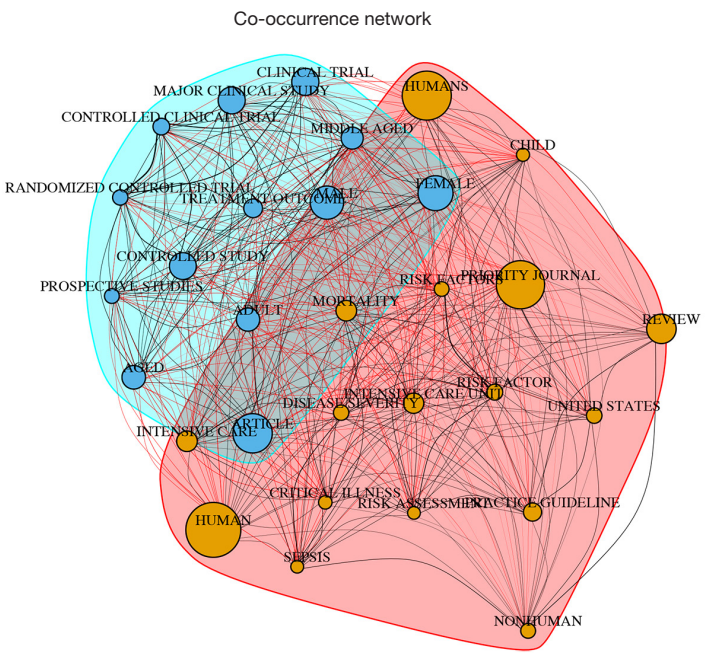

Figure 5 Co-occurrence of keywords with Fruchterman-Reingold layout. The size of nodes represents the frequency of occurrence. The edges between nodes indicate their co-occurrence in the same document. It showed that studies involving human subject were the most common literature type. Sepsis was a major research area, and the word sepsis co-occurred with keywords such as disease severity, nonhuman, risk assessment and practice guideline. The Walktrap algorithm identified two clusters from the keywords pool. The two clusters were represented by blue and yellow colors in the nodes. The blue cluster involved clinical trials investigating effective of a treatment on clinical outcomes. The yellow cluster involved studies investigating risk factors or disease severity studies.

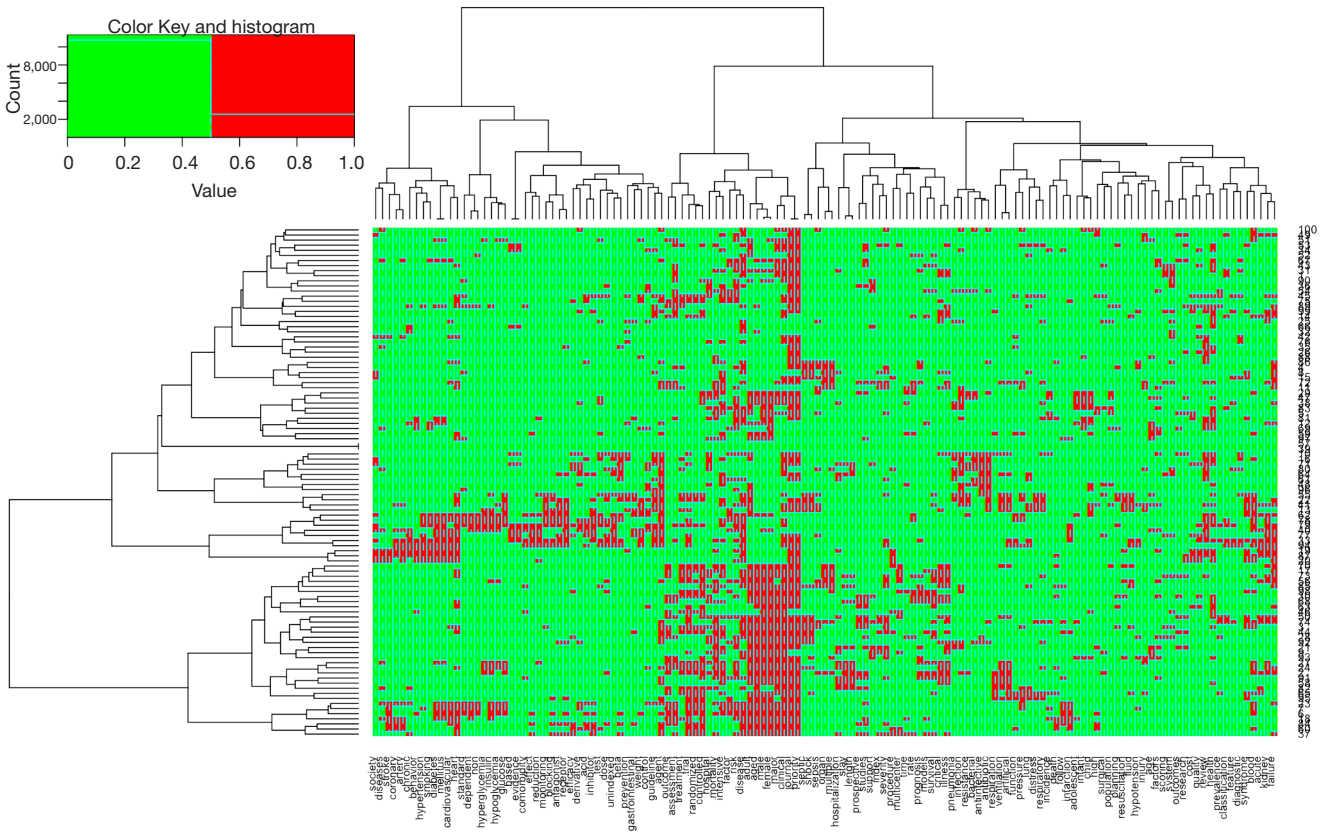

Figure 6 Heat map and hierarchical analysis of keywords. There was a cluster involving the study of diabetes mellitus and cardiovascular diseases in critical care medicine. Another cluster is clinical trials investigating risk factors of mortality outcome. Sepsis and septic shock formed a smaller cluster.

of CCM. These documents were cited by a median of 386 times [interquartile range (IQR): 308–562 times]. The most highly cited article was the one developed the APACHE II score (15); the score was the most widely used for assessment of disease severity in critical care benchmarking and clinical studies. Some clinical practice guidelines involving sepsis and acute renal failure were among the top 10 most cited articles (18,19,23). The most important journal for publishing highly cited critical care documents was the journal CCM, which published 217 highly cited documents. The nine important journals for the publication of critical care highly cited literature were *NEJM*, *JAMA*, *CCM*, *Critical Care*, *Intensive Care Medicine*, *Pediatrics*, *British Medical Journal*, the *Lancet* and *Chest*. Our bibliometric analysis focused primarily on the keywords of the included articles. The most frequently used keywords were human, female, male, humans, priority journal and articles in the CCM literature. Some study clusters such as studies involving diabetes mellitus and cardiovascular diseases, and sepsis and septic shock were identified by hierarchical analysis.

Bibliometric analysis has also been performed in the past in many areas of CCM such as on severe traumatic brain injury by Li and colleagues (6). In that study, the authors provided general descriptive data on the 100 top cited articles on severe traumatic brain injury. Their top 100 articles were cited on average 326.4 times, which approximated to the statistics in our study. Since our topic of bibliometric analysis was broader, our study has more highly cited articles than in Li's study. Tao and colleagues reviewed the top 50 cited clinical papers on the topic of sepsis and found that the number of citations ranged from 372 to 2,932, with a mean of 678 citations per article. The 50 top cited articles were published in 17 journals, with the *NEJM* and *JAMA* were at the top of the list (7). In our analysis, the top cited article was published in the *Critical*

Figure 7 Word cloud showing the frequency of the occurrence of a keyword. Keywords such as "intensive care unit", "mortality", "critical illness" and "length of stay" were the most commonly occurred keywords.

Care Medicine journal, followed by *NEJM* and *Chest*. The *Critical Care Medicine* journal published the largest number of highly cited articles. In another bibliometric analysis investigating the top 100 cited articles in acute kidney injury, Liu and colleagues found that the top 100 articles originated from 15 countries, led by the US (n=81) (8). This is consistent with our study that authors from the US published more than half of the most highly cited articles in general.

Keywords analysis has yet been performed in the previously mentioned bibliometric analyses. The Walktrap algorithm was employed in our study to find clusters with the most connections. We found that a major cluster is a group of clinical studies that investigated therapeutic interventions on clinical outcomes. Clinical trials in critical care involve a heterogeneous subject population, imposing a greater challenge for investigators. Therefore, a simple clinical question usually requires extensively external validations because the characteristics of critically ill patients can vary remarkably across institutions and countries. For example, the EGDT was initially found to be beneficial for septic shock (16), which however, was not verified

in subsequent clinical trials (24-26). This reflects the complexity of the intervention, as well as the heterogeneity of critically ill patients (27). Thus, results from clinical trials are always considered first to make the treatment standards for a disease process. As a result, efficacy trials are among the most common types of literature cited in in CCM.

Lotka's law is an important index in bibliometric analysis, which investigates the relationship between the number of publications and authors. In Lotka's seminal paper {Lotka:1926vc}, he found that "*the number (of authors) making contributions is about* $1/x^2$ *of those making one; and the proportion of all contributors, that make a single contribution, is about 60 percent*". Originally developed in chemistry and physics in early 20th century (28), the Lotka's law is also called as the inverse square law. In the field of library and information studies, the values of n and c were assigned to be 2.1 and 0.6418 (64.18%) respectively, which conformed to Lotka's law. In a 2008 article by Askew *et al.* {Askew:2008kd}, the authors concluded that "*Lotka's law can be used in library and information studies as a standardized means of measuring author publication productivity which will lead to findings that are comparable on many levels*" (29). In the field of CCM, the n and c value differed significantly from the Lotka's law, which may not be suitable for the measurement of authors' productivity.

This study has limitations. The contributions of authors were not equal in a given article. However, there was no objective index to measure relative contribution of an author; thus, this factor was not investigated in the present study. The bibliographic database used in our study was Scopus, whose indexed journals may not cover all in the field of CCM, and the results may be different from analysis based on other bibliographic databases. Although Web of Science is well known for its high-quality inclusion criteria for journals, Scopus includes more source titles and is more likely to reflect bibliometric performance. CCM includes many sub-specialties such as acute kidney injury, sepsis and organ dysfunctions. Including all sub-specialties may mask some characteristics of bibliometric profile. Future studies may focus on specific sub-specialties of CCM by using co-occurrence and cluster analysis.

In conclusion, this study performed bibliometric analyses of 2,000 top cited articles in the field of CCM. The most highly cited article was about the description of APACHE II score. Some hot spots such as blood glucose control, sepsis, septic shock, mortality was identified via co-occurrence and clustering analysis. Author's productivity differs significantly when analyzed by the Lotka's law.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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