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Quality vs. quantity of publications in nanotechnology field from the People's Republic of China

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This study evaluates trends in quality of nanotechnology and nanoscience papers produced by authors from the People's Republic of China (PRC). The metric used to gauge quality is ratio of highly cited nanotechnology papers to total nanotechnology papers produced in sequential time frames. The USA is both the most prolific nanotechnology publishing country and most represented country on highly cited nanotechnology papers (both in absolute numbers of highly cited papers and highly cited papers relative to total publications) over the 1998—2003 time frame, based on the SCI/SSCI databases. Some of the smaller hi-tech countries have relatively high ratios (~2) of highly cited papers to total publications (e.g. Denmark, Netherlands, Switzerland). Countries that have exhibited rapid growth in SCI/SSCI nanotechnology paper production in recent years (e.g. PRC, South Korea) had ratios an order of magnitude less than that of the USA for 1998, but by 2003 had increased to about 20% that of the USA (~2.5). PRC and South Korea have climbed in the publications rankings from 6th and 9th in 1998, respectively, to 2nd and 6th in 2005, respectively. PRC's ratio monotonically increased from 0.16 to 0.45 over the 1998—2003 period, and South Korea's ratio increased from 0.11 to about 0.6 over that same period, indicating their papers are getting more and more citations proportionately. Thus, under rapid growth conditions, PRC and South Korea have been able to increase their share of participation in highly cited papers. As of 2003, PRC and South Korea have ratios comparable to nations like Japan, France, Italy, and Australia but not yet approaching those of the highly cited countries. None of the top ten publications producing institutions are from the USA, while all of the top ten highly cited publications producers are from the USA. Over the 1998—2003 time period, the top six total publications producing institutions (globally) remained the same, with Chinese Academy of Sciences (which consists of many research institutes) wresting the lead from Russian Academy of Sciences in 1999, and thereafter increasing the gap. Over this same time period, the USA institutions constituted about 90% of the top ten most cited papers list. For Chinese institutions specifically in the period 1998—2003, the nanotechnology publication leading Chinese Academy of Sciences has maintained an average of about 30% of nanotechnology publications over that time frame. The second tier (in terms of quantity) for the last few years has consisted of Tsinghua University, Nanjing University, University of Science and Technology of China, Peking University, Jilin University, Zhejiang University, Shandong University, and Fudan University. Hong Kong institutions have, on average, been strong in ratio, especially City University Hong Kong, and Hong Kong University of Science and Technology, indicating significant citations.

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Nanotechnology is the development and use of techniques to study physical phenomena and construct structures in the physical size range of 1—100 nm, as well as the incorporation of these structures into applications. Globally, nanotechnology research publications have grown exponentially for more than a decade[1]. Nanotechnology publications and citations have been used to show infrastructure bibliometrics[1−3], science to technology linkages[4], mapping relationships[5], and point examples of highly cited papers to overall production[6,7].

There appear to be no examples of temporal trends of ratios of highly cited nanotechnology/nanoscience papers to total nanotechnology/nanoscience papers, where the ratios are computed over small periods of time. We believe this type of analysis is important for organizations/countries that are experiencing rapid growth. In this case, aggregate ratios of highly cited papers to total papers over a long period of time may be misleading due to the large number of recent papers that contribute to the total publication statistics but have not yet had time to generate citations.

The present paper examines temporal quantity-quality relationships for the leading nanoscience and nanotechnology research output producers, with detailed emphasis on PRC institutions. The PRC has had a strategic commitment to science and technology in general, and nanoscience and nanotechnology in particular, for the last decade. Ref. [8] summarizes the PRC's commitment to supporting science and technology in nanoscience and nanotechnology, and the reflection of this commitment in research output growth. Ref. [9] shows PRC's strongly increasing contribution to world science, with substantial increases in citation rates as well. Further, PRC's global share of nanoscience and nanotechnology publications is shown to be higher than its overall global science and technology share, reflecting very high growth for nanoscience and nanotechnology as well. Ref. [10], a bibliometric analysis of PRC's nanoscience and nanotechnology research output, confirms the rapid growth of PRC's nanoscience and nanotechnology research output, but concludes that PRC's total citation rate is low compared with citation rates for other nations.

The conclusions in the previous paragraph are confirmed by the detailed findings in Ref. [1], which used the most comprehensive nanoscience and nanotechnology query existing today. From 1991 to 2005, PRC increased its production of nanotechnology papers forty-fold in the SCI/SSCI[1], where it was second to the USA in total nanotechnology publications in 2005. Recent unpublished computations by the first author have shown that, for the first half of 2007: (i) The PRC nanotechnology publications in the SCI/SSCI are within ~10% of those of the USA, and (ii) the PRC nanotechnology publications in the EI Compendex (an applied science and technology development database) lead those of the USA by almost a factor of two.

How did the quality of the PRC's nanotechnology publications change under such high publication growth conditions, and in particular, what were the quantity-quality relationships at the leading institutions?

To place the PRC results in their larger context, we will first start by examining how the major nanotechnology producing countries have fared with respect to quality over the past decade. Then, we will examine how the major nanotechnology producing institutions globally have fared with respect to quality over the same time frame, and where the major PRC institutions are positioned with respect to the global leaders. Finally, we will examine how the major nanotechnology paper producing institutions in PRC have fared with respect to quality.

The quality metric employed for this analysis is the efficiency of highly cited nanotechnology document production; i.e. the ratio of highly cited nanotechnology documents produced to overall nanotechnology documents produced. We define a citation threshold for highly cited nanotechnology documents as the top 1% of total nanotechnology publications (for the global analysis). For each country, or institution, we calculate the number of highly cited papers that it has produced in selected time frames of interest, then take the ratio of this number to total number of publications the entity has produced over the selected time frame, and use this as our Figure of Merit.

In the first part of this paper, citations (and publications) for nanotechnology documents published by major producing nations and major producing global institutions in four uneven time frames were examined. All nanotechnology documents in the Science Citation Index for 1998, 1999—2000, 2001—2002, 2003 were retrieved using a 300+ term query[11] and analyzed in March—June 2007.

In the second part of this paper, all the nanotechnology documents produced by PRC institutions were retrieved and examined. For each PRC institution, the fraction of total highly cited documents was compared with their fraction of total published documents. Non-PRC institutions that co-authored papers were included as well, to offer some perspective on the value of collaboration.

The distributions of numbers of publications among institutions and countries were computed, the most highly cited publications were extracted, and the country and institution distributions for the highly cited documents were generated. The country and institution publication distributions were then compared with the citation distributions. This allowed a comparison of countries and institutions with high number of citations relative to the number of their publications (and thus were producing highly cited papers more efficiently than their publication statistics would predict), as well as institutions whose citation fractions were less than their publication fractions.

1 Nanotechnology query development

Key to the quality of these results is the query used to retrieve nanotechnology articles from the SCI/SSCI. The query used had three components: phrases used to search the unstructured text fields (title/abstract/keywords); phrases used to search the journal title field; and phrases used to search the address field. The phrases used to search the unstructured text fields were obtained by an iterative relevance feedback approach, and numbered over 300. This component took weeks to generate. The journals were all those that included nano∗ in the title, and the addresses were essentially all those with nano∗ in the address.

The 300+ term query used to search the SCI/SSCI was also used to search the unstructured text fields in the EI Compendex database. In addition, the other EI Compendex fields were searched for all terms that contained nano∗. These included controlled vocabulary, controlled heading, journal, and address fields, in which nano∗ meant nanotechnology-type terms. The classification codes field was searched for code 761, the nanotechnology code.

All terms in the query were checked for retrieval precision, and any term that retrieved less than 85% relevant articles was excluded. The full SCI/SSCI query is presented in ref. [11].

2 Results

2.1 Production efficiency of highly cited nanotechnology papers by nations

Because of space considerations, only tables for 2003 will be shown, a summary temporal trend figure will be presented for each sub-section, and results for 1998—2003 will be discussed. Table 1 contains the country distributions for 2003. A country publication means that it was listed in the address field of the publication; other countries may have been listed as well. The left side is the total publications ranked by country, and the right side is the number of highly cited publications (top 1%) again ranked by country. On either side, the first column is the country, the second column (Rec Count) is number of SCI/SSCI records, the third column (CIT%) is the country's highly cited papers as a percentage of the total highly cited papers, the fourth column (PUB%) is the country's published papers as a percentage of total published papers in that year, and the last column (CIT/PUB) is the ratio of highly cited papers fraction to total papers fraction.

As an example, in 2003 there were 480 most cited papers. The USA at 300 record count produced 62.5% (300/480) of the most cited nanotechnology papers, and the USA produced 11408 papers out of the total 47945 papers, or 23.79% (11408/47945) of total nanotechnology papers. Thus, the USA is both the most prolific nanotechnology publishing country and most represented country on highly cited nanotechnology papers for 2003. Its ratio of percent representation on most highly cited nanotechnology papers to percent of total nanotechnology publications (ratio = 62.5/23.79) is 2.63. A ratio greater than one means that a country has higher representation on most cited papers than would be expected from its publications alone. A ratio less than one means that a country has lower representation. In other words, a higher than one ratio means that country's papers are cited more often relative to the number of papers it publishes. A ratio of 2.63 for the USA means that the USA representation on most highly cited records is 2.63 times what would be expected based on the number of nanotechnology publications alone.

None of the other large producers has ratios approaching that of the USA (for 2003 publications), and only some of the smaller hi-tech countries have ratios of

Table 1 Country distributions-overall records/top 1% cited records (2003)

Total records 47945					Most cited: 1% = 480 records (73 CITES MIN)				
Country/Territory	Rec Count	CIT (%)	PUB (%)	CIT/PUB	Country/Territory	Rec Count	CIT (%)	PUB (%)	CIT/PUB
USA	11408	62.50	23.79	2.63	USA	300	62.50	23.79	2.63
Japan	7196	6.67	15.01	0.44	Germany	48	10.00	10.24	0.98
People's R China	6717	6.25	14.01	0.45	Japan	32	6.67	15.01	0.44
Germany	4911	10.00	10.24	0.98	UK	32	6.67	5.85	1.14
France	3338	3.75	6.96	0.54	People's R China	30	6.25	14.01	0.45
UK	2805	6.67	5.85	1.14	France	18	3.75	6.96	0.54
South Korea	2640	3.13	5.51	0.57	Netherlands	17	3.54	1.74	2.04
Russia	2015	0.42	4.20	0.10	Switzerland	16	3.33	1.68	1.99
Italy	1803	2.29	3.76	0.61	South Korea	15	3.13	5.51	0.57
India	1498	0.63	3.12	0.20	Spain	14	2.92	2.69	1.09
Spain	1288	2.92	2.69	1.09	Italy	11	2.29	3.76	0.61
Taiwan	1234	0.42	2.57	0.16	Israel	9	1.88	1.06	1.77
Canada	1193	0.83	2.49	0.33	Sweden	9	1.88	1.67	1.12
Poland	857	0.21	1.79	0.12	Denmark	7	1.46	0.62	2.35
Netherlands	834	3.54	1.74	2.04	Austria	6	1.25	0.95	1.32
Switzerland	804	3.33	1.68	1.99	Australia	5	1.04	1.60	0.65
Sweden	803	1.88	1.67	1.12	Belgium	4	0.83	1.20	0.69
Australia	768	1.04	1.60	0.65	Brazil	4	0.83	1.57	0.53
Brazil	755	0.83	1.57	0.53	Canada	4	0.83	2.49	0.33
Singapore	662	0.83	1.38	0.60	Singapore	4	0.83	1.38	0.60

two or greater (Denmark, Netherlands, Switzerland). Countries that have exhibited rapid growth in SCI/SSCI nanotechnology paper production in recent years (e.g. PRC, South Korea) had ratios an order of magnitude less than that of the USA for 1998, but by 2003 had increased to about 20% that of the USA. The lowest tier for 1998 consisted of Belgium, Poland, Taiwan territory, and India, and by 2003 the lowest tier included Russia, Poland, Taiwan territory, and India.

For 1999－2000, the USA remained dominant in nanotechnology publications and representation on most highly cited nanotechnology papers in ratio as well. Switzerland and the Netherlands remained on par with the US, but Israel dropped in ratio while Canada moved up. For 2001－2002, the US at 2.50 remains dominant in the ratio of CIT/PUB, without any other country coming even close.

Over the total time frame from 1998－2003, the USA's performance was remarkably consistent, with about 25% of total nanotechnology publications and about 60% of total highly cited papers. Its ratio hovered around 2.5. Switzerland and Netherlands maintained reasonably high ratios, and except for one time period, so did Israel and Denmark.

Of the other large producers of publications, Japan hovered around a ratio of about 0.5, indicating that its papers are less cited, on average, than one would expect from the large number of papers, although there may be individuals who are cited highly. Germany climbed slightly to a ratio near unity, the UK hovered around a ratio of unity, and thus the citations are as one would expect: proportional to the number of papers published. France oscillated around a ratio of about 0.65. Russia had a remarkably consistent ratio of about 0.37, but dropped recently to 0.10. Poland and Taiwan territory have remained consistently very low.

PRC and South Korea have climbed in the publications rankings from 6th and 9th in 1998, respectively, to 3rd and 7th in 2003, respectively (and to 2nd and 6th in 2005, respectively[1]). PRC's ratio monotonically increased from 0.16 to 0.45 over the 1998－2003 period, and South Korea's ratio increased from 0.11 to about 0.6 over that same period, indicating their papers are getting more and more citations proportionately. Thus, under rapid growth conditions, PRC and South Korea have been able to increase their share of participation in highly cited papers. As of 2003, PRC and South Korea have ratios comparable to nations like Japan, France, Italy, and Australia but not yet approaching those of the highly cited countries. This can be seen more graphi-

cally in Figure 1, where ratio is plotted vs. time for selected countries.

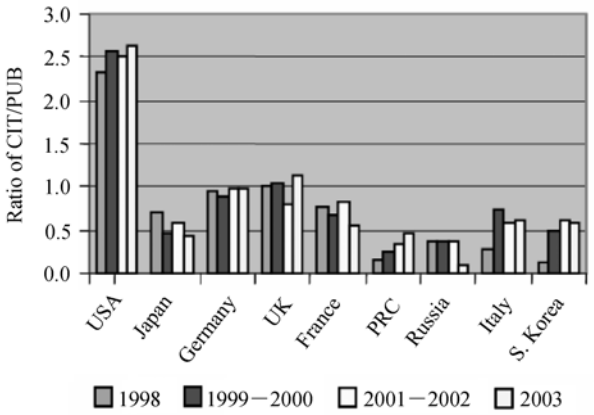

Figure 1 Ratio of citation percentage over publication percentage from 1998 to 2003.

The numbers for PRC and South Korea have to be viewed in a larger context. For technology and engineering development, it is very important to have a trained cadre of researchers available to address the research issues that inevitably arise in the course of development. It is not necessary for these researchers to all be highly cited authors in order for them to have substantial value for supporting and accelerating technology and engineering development. If researchers are of the caliber to publish in the high quality journals typically accessed by the SCI/SSCI, they can offer expert assessment of what is being produced globally, and can exploit this cutting edge research in the development process.

Thus, if PRC and South Korea are increasing the numbers of nanotechnology researchers rapidly, and if their participation in highly cited papers is increasing at the same time, this rapid and increasing quality growth translates into a powerful foundation for accelerated growth in the industrial capability of their national development in the future. They are building a strong foundation not only for enhanced research quantity and quality capability, but for the more commercially and militarily important industrial capability as well.

2.2 Production efficiency of highly cited nanotechnology papers by global institutions

Table 2 lists the global institutions that produced the most nanotechnology publications and institutions that produced the most highly cited (top 1%) publications. It has the same structure as Table 1, and reflects data for 2003. The temporal trend for selected institutions that have remained strong publications producers is shown in Figure 2.

Table 2 Global institution distributions-overall records/top 1% cited records (2003)

Total records 47945					Most cited: 1% = 480 records (73 CITES MIN)				
Institution name	Rec Count	CIT (%)	PUB (%)	CIT/PUB	Institution name	Rec Count	CIT (%)	PUB (%)	CIT/PUB
Chinese Acad Sci	1894	1.88	3.95	0.47	Univ Calif Berkeley	22	4.58	0.69	6.66
Russian Acad Sci	1110	0.21	2.32	0.09	Harvard Univ	19	3.96	0.40	9.78
CNRS	627	1.04	1.31	0.80	Northwestern Univ	17	3.54	0.48	7.45
Univ Tokyo	588	1.04	1.23	0.85	Georgia Inst Technol	16	3.33	0.42	7.91
Tohoku Univ	564	0.63	1.18	0.53	MIT	16	3.33	0.67	4.98
Osaka Unic	555	0.63	1.16	0.54	Rice Univ	15	3.13	0.29	10.70
Natl Inst Adv Ind Sci & Technol	527	0.21	1.10	0.19	Univ Washington	12	2.50	0.33	7.49
Tsinghua Univ	509	1.25	1.06	1.18	Stanford Univ	11	2.29	0.37	6.14
Tokyo Inst Technol	462	0.00	0.96	0.00	IBM Corp	10	2.08	0.32	6.52
Natl Inst Mat Sci	429	0.21	0.89	0.23	CALTECH	9	1.88	0.26	7.08
Seoul Natl Univ	391	1.04	0.82	1.28	Chinese Acad Sci	9	1.88	3.95	0.47
Univ Illinois	388	1.88	0.81	2.32	Univ Calif Los Angeles	9	1.88	0.27	6.86
CNR	384	0.83	0.80	1.04	Univ Illinois	9	1.88	0.81	2.32
Nanjing Univ	377	0.21	0.79	0.26	USN	9	1.88	0.43	4.36
Univ Ccmbridge	373	1.46	0.78	1.87	NASA	7	1.46	0.34	4.29
Univ Sci & Technol China	367	0.42	0.77	0.54	Oak Ridge Natl Lab	7	1.46	0.47	3.11
Kyoto Univ	362	1.04	0.76	1.38	Univ Calif Santa Barbara	7	1.46	0.46	3.19
Natl Univ Singapore	360	0.83	0.75	1.11	Univ Cambridge	7	1.46	0.78	1.87
CSIC	347	1.46	0.72	2.02	CSIC	7	1.46	0.72	2.02
Univ Texas	346	1.46	0.72	2.02	Univ Florida	7	1.46	0.43	3.38
Univ Calif Berkeley	330	4.58	0.69	6.66	Univ Texas	7	1.46	0.72	2.02

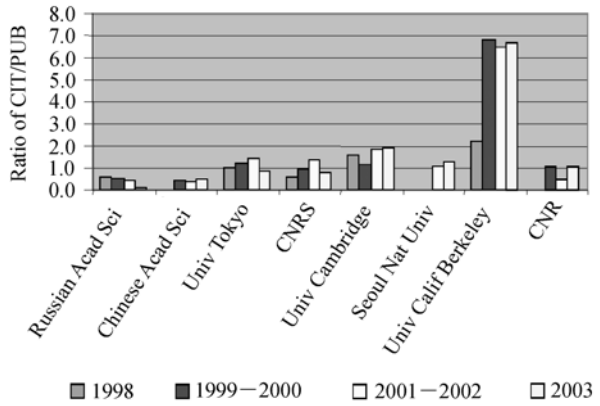

Figure 2 Ratio of citation percentage over publication percentage for institutions.

Of the top ten publications producers, none are from the USA. The top seven producers all have ratios below unity. The twelfth ranked University of Illinois has a respectable 2.32 ratio, twentieth ranked University of Texas has a good ratio of 2.02, and 21st ranked University of California at Berkeley has a very high ratio of 6.66. For the top ten highly cited publications producers, a different picture from that of the top ten publications producers emerges. All of the top ten highly cited institutions are from the USA. All of the USA institutions in the highly cited side have ratios above 2. Harvard and Rice have exceptionally high ratios, hovering around ten. These institutions have highly cited papers relative to the total number of citations.

A word about institution aggregation. The SCI Analysis function, which is used for validation purposes only, aggregates all the USA state academic institution campuses into one unit for each state, except for California. Thus, the University of Illinois at Champaign-Urbana, University of Illinois at Chicago, etc., are aggregated into University of Illinois. However, University of California at Berkeley et al. are treated as separate institutions. The SCI Analysis function also aggregates other large institutions as well, with the exception of the Max Planck institutes. We chose to follow this aggregating convention. If the University of California campuses were combined into one state unit, they would dominate the other institutions in both number of total papers and number of highly cited papers. If the Max Planck institutes were combined into one unit, they would appear on this table, although not as dominant as the University of California.

Over the 1998－2003 time period, the top six total publications producers remained the same, with Chinese Academy of Sciences (which consists of many research institutes) wresting the lead from Russian Academy of Sciences in 1999, and thereafter increasing the gap. Over this same time period, the USA institutions constituted about 90% of the top ten most cited papers list. Harvard and UCB vied for the lead over this period. Harvard and Rice maintained ratios typically above 10 in this period. In 1998, there were eight USA institutions on the list of most publications producers, and by 2003 only three were left. This is a consequence of the rapid production growth rate of the Asian institutions.

Two institutions that seem to have plummeted in ratio are the Russian Academy of Sciences (0.55 in 1998 monotonically to 0.09 in 2003) and Tokyo Institute of Technology (1.94 in 1998 almost monotonically to 0 in 2003). Kyoto University, on the other hand, increased its ratio almost monotonically from 0 in 1998 to 1.38 in 2003. The major Chinese producing institution, Chinese Academy of Sciences, grew from a ratio of 0 in 1998 to ~0.5 in 2003, and China's second major producer, Tsinghua University, grew from 0.28 in 1999－2000 to 1.18 in 2003. Korea's major producer, Seoul National University, grew from a negligible ratio in 1998 (not shown) to a ratio of 1.28 in 2003. This was accompanied by a growth in total publications over that period from negligible in 1998 to 391 in 2003. Thus, the leading Chinese and South Korean institutions not only increased their total publications production rapidly, but increased quality as well. While they are not in the quality league of the leading USA institutions, they are making steady progress.

2.3 Production efficiency of highly cited nanotechnology papers by PRC institutions

The first section of this paper is a global comparison of nanotechnology paper production at the national level and at the major institutional level. The present section addresses the next level of detail, a national comparison at the institutional level.

We used the same approach as in the first section, with the same metrics. The one difference is that we lowered the threshold for highly cited papers (from top 1% to top 2.5%) in order to get adequate statistics.

Table 3 presents the PRC institutional results for 2003. Additionally, institutions from other countries are in this table because there is collaboration and co-authorship with researchers in PRC. The temporal trend for selected

Table 3 Chinese institution distributions-overall records/top 1% cited records (2003)

Total records 6717					Most cited: 2.5% (39 CITES MIN)				
Institution name	# Rec	CIT (%)	PUB (%)	CIT/PUB	Institution name	# Rec	CIT (%)	PUB (%)	CIT/PUB
Chinese Acad Sci	1893	31.74	28.18	1.13	Chinese Acad Sci	53	31.74	28.18	1.13
Tsinghua Univ	508	13.77	7.56	1.82	Tsinghua Univ	23	13.77	7.56	1.82
Nanjing Univ	377	2.99	5.61	0.53	Peking Univ	15	8.98	4.48	2.00
Univ Sci & Technol China	367	7.19	5.46	1.32	Univ Sci & Technol China	12	7.19	5.46	1.32
Peking Univ	301	8.98	4.48	2.00	City Univ Hong Kong	10	5.99	2.08	2.87
Jilin Univ	288	1.80	4.29	0.42	Hong Kong Univ Sci & Technol	10	5.99	2.44	2.45
Zhejiang Univ	238	1.20	3.54	0.34	Zhongshan Univ	10	5.99	2.13	2.81
Shandong Univ	231	1.80	3.44	0.52	Univ Hong Kong	8	4.79	1.43	3.35
Fudan Univ	173	2.99	2.58	1.16	Fudan Univ	5	2.99	2.58	1.16
Hong Kong Univ Sci & Technol	164	5.99	2.44	2.45	Nanjing Univ	5	2.99	5.61	0.53
Shanghai Jiao Tong Univ	163	0.60	2.43	0.25	Chinese Univ Hong Kong	4	2.40	1.15	2.09
Zhongshan Univ	143	5.99	2.13	2.81	Georgia Inst Technol	4	2.40	0.21	11.49
City Univ Hong Kong	140	5.99	2.08	2.87	Nankai Univ	4	2.40	1.74	1.38
Nankai Univ	117	2.40	1.74	1.38	NE Normal Univ	4	2.40	1.13	2.12
Harbin Inst Technol	112	0.00	1.67	0.00	Beijing Inst Technol	3	1.80	0.68	2.62
Wuhan Univ	106	1.80	1.58	1.14	Dalian Univ Technol	3	1.80	0.94	1.92
Tianjin Univ	98	0.00	1.46	0.00	Jilin Univ	3	1.80	4.29	0.42
Hong Kong Polytech Univ	97	1.20	1.44	0.83	Shandong Univ	3	1.80	3.44	0.52
Univ Hong Kong	96	4.79	1.43	3.35	Univ Akron	3	1.80	0.18	10.05
Univ Sci & Technol Beijing	85	1.20	1.27	0.95	Wuhan Univ	3	1.80	1.58	1.14

institutions that have remained strong publications producers is shown in Figure 3.

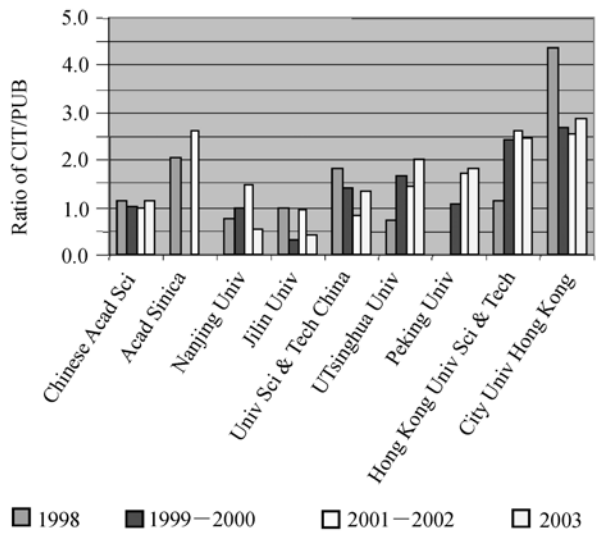

Figure 3 Ratio of CIT/PUB for Chinese institutions.

For the period 1998－2003, the consistent leader in terms of numbers of publications has been the Chinese Academy of Sciences. It has maintained an average of about 30% of publications over that time frame. The second tier (in terms of quantity) for the last few years has consisted of Tsinghua University, Nanjing University, University Science and Technology China, Peking University, Jilin University, Zhejiang University, Shandong University, and Fudan University. Academica Sinica (Taiwan) has declined monotonically in publications from ~8.5% in 1998 to ~1% in 2003 (and its ratio over the same period has also declined from ~2.0 to 0.5). Over the same period, Tsinghua Univ has increased its fraction of publications monotonically from ~5% to ~7.5%. In parallel, it has monotonically increased its ratio from 0 to ~1.8. In terms of numbers of highly cited papers, the first two publication tiers are also, for the most part, the first two citation tiers.

Hong Kong institutions have, on average, been strong in ratio, especially City University of Hong Kong, and Hong Kong University of Science and Technology.

Foreign institutions that appear in the tables typically have high ratios. Examples with more than one highly cited paper include GM Corp (1998), MIT (1998－2000), Tohoku University (1998), National University of Singapore (1998 － 2000), Bar Ilan University (1999－2000), Georgia Institute of Technology (1999－2000, 2003), Nagoya University (1999－2000), UCSB (1999－2000), University of Cambridge (1999－2000), University of Technology Troyes (1999－2003), Washington University (1999 － 2000), McGill University

(2001－2003), Medical College of Georgia (2001－2002), University of Illinois (2001－2002), University of Tokyo (2001－2003), and University of Akron (2003).

Clearly, collaboration of Chinese institutions with foreign institutions, on average, is the path to highly cited papers for nanotechnology research. While this conclusion was reached for nanotechnology research, a recent text mining study on China's total science and technology enterprise[12] corroborates this conclusion for all areas of science and technology. Specifically, the impact of collaboration was substantial on the top ten cited articles published from 1995－1999 with at least one Chinese author (median citations of top ten cited articles retrieved with collaboration, 604; median citations of top ten cited articles retrieved without foreign collaboration, 239), and was noticeable on the top five percent of cited articles published from 1995－1999 with at least one Chinese author (median citations of top 5% articles retrieved, 35; median citations of top 5% articles retrieved, 25).

Institutions with moderate publication rates and consistently low ratios include Zhejiang University (~ <0.5), Shanghai Jiao Tong University (~0.6, or much less), and Shandong University (except for 1998). Chungnam National University started with a high ratio in 1998, but has had a very low ratio since that time.

In summary, the major publications producer (Chinese Academy of Sciences) has maintained reasonable ratios of highly cited documents to total nanotechnology publications under high growth conditions. Most other institutions, with exceptions noted above, have exhibited ratio swings over time, some quite large. Papers with foreign institution participation tend to have high citation performance.

2.4 Future directions

The trends identified in this study are interesting, and raise questions that need to be addressed in further studies. First, publication numbers are presented in the absence of resources required to generate these publications. Studies are required to identify the funds and numbers of researchers associated with these publication numbers, so that publication efficiencies can be obtained.

Second, the research thrust areas need to be correlated with the cost of doing research. Some research thrust areas may be dependent on the purchase of expensive research equipment, and thus are more expensive for conducting the research. This could help to explain unusual publication trends. Correlating citation/publication ratios with the costs of nanotechnology disciplines pursued might shed some light on causes for highly cited papers.

Third, the research thrust areas associated with the various ratios of highly cited papers to numbers of total publications need to be identified. This would help differentiate the component of highly cited paper production due to intrinsic researcher quality from the component due to having selected popular topics.

Finally, databases other than the SCI need to be examined in detail. Our brief examination of the EI Compendex showed China's nanotechnology paper production performance to be superior to its very commendable performance in the SCI, especially relative to that of the USA. The USA is the global leader in biomedical research, and the SCI contains a strong biomedical component. For databases that emphasize physical and engineering sciences, such as the EI Compendex (or Inspec), the relative performance of China and USA with respect to nanotechnology paper production in physical and engineering sciences may be more accurate. More detailed analysis of EI Compendex and Inspec are necessary to validate these hypotheses.

3 Summary and conclusions

We have examined temporal trends in the ratio of highly cited nanotechnology/nanoscience papers to total nanotechnology/nanoscience papers for countries, global institutions, and PRC institutions. PRC and South Korea have climbed rapidly in the publications rankings. PRC's ratio has monotonically increased from 0.16 to 0.45 over the 1998－2003 period, and South Korea's ratio has increased from 0.11 to about 0.6 over that same period, indicating their papers are getting more and more citations proportionately. Thus, under rapid growth conditions, PRC and South Korea have been able to increase their share of participation in highly cited papers. As of 2003, PRC and South Korea have ratios comparable to nations like Japan, France, Italy, and Australia but not yet approaching those of the highly cited countries.

For global institutions, of the top ten publications producers, none are from the USA in 2003. However, all

of the top ten highly cited institutions are from the USA in 2003.

Over the 1998－2003 time period, the top six total publications producers remained the same, with Chinese Academy of Sciences (which consists of many research institutes) wresting the lead from Russian Academy of Sciences in 1999, and thereafter increasing the gap. Over this same time period, the USA institutions constituted about 90% of the top ten most cited papers list. Harvard and UCB vied for the lead over this period

The major PRC producing institution, Chinese Academy of Sciences, grew from a ratio of 0 in 1998 to ~0.5 in 2003, and PRC's second major producer, Tsinghua University, grew from 0.28 in 1999－2000 to 1.18 in 2003. Korea's major producer, Seoul National University, grew from a negligible ratio in 1998 (not shown) to a ratio of 1.28 in 2003. This was accompanied by a growth in total publications over that period from negligible in 1998 (not shown) to 391 in 2003. Thus, the leading PRC and South Korean institutions not only increased their total publications production rapidly, but increased quality as well. While they are not in the quality league of the leading USA institutions, they are making steady progress.

For PRC institutions specifically, the major publications producer (Chinese Academy of Sciences) has maintained a reasonable and consistent ratio of highly cited documents to total nanotechnology publications under high growth conditions. Most other PRC institutions, with exceptions noted above, have exhibited ratio swings over time, some quite large. Papers with co-authors from non-PRC institutions tend to have high citation performance, indicating the value of international collaboration.

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