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ORIGINAL ARTICLE

Trends and hot topics in radiology, nuclear medicine and medical imaging from 2011–2021: a bibliometric analysis of highly cited papers

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Abstract

Purpose To spotlight the trends and hot topics looming from the highly cited papers in the subject category of *Radiology, Nuclear Medicine & Medical Imaging* with bibliometric analysis.

Materials and methods Based on the Essential Science Indicators, this study employed a bibliometric method to examine the highly cited papers in the subject category of *Radiology, Nuclear Medicine & Medical Imaging* in Web of Science (WoS) Categories, both quantitatively and qualitatively. In total, 1325 highly cited papers were retrieved and assessed spanning from the years of 2011 to 2021. In particular, the bibliometric information of the highly cited papers based on WoS database such as the main publication venues, the most productive countries, and the top cited publications was presented. An Abstract corpus was built to help identify the most frequently explored topics. VoSviewer was used to visualize the co-occurrence networks of author keywords.

Results The top three active journals are *Neuroimage, Radiology* and *IEEE T Med Imaging*. The *United States, Germany* and *England* have the most influential publications. The top cited publications unrelated to COVID-19 can be grouped in three categories: *recommendations or guidelines, processing software,* and *analysis methods*. The top cited publications on COVID-19 are dominantly in *China*. The most frequently explored topics based on the Abstract corpus and the author keywords with the great link strengths overlap to a great extent. Specifically, phrases such as *magnetic resonance imaging, deep learning, prostate cancer, chest CT, computed tomography, CT images, coronavirus disease, convolutional neural network(s)* are among the most frequently mentioned.

Conclusion The bibliometric analysis of the highly cited papers provided the most updated trends and hot topics which may provide insights and research directions for medical researchers and healthcare practitioners in the future.

Keywords Bibliometric analysis · Radiology · Nuclear medicine · Medical imaging · Highly cited papers

Introduction

Citation distributions are extremely skewed. Most scientific papers are seldom cited, if ever, in the subsequent scientific literature while some papers receive an unusually high citation counts [1]. In the past decade, there has been a growing interest in using highly cited papers as indicators in research assessments. There may be two reasons for this tendency. First, the increasing focus on scientific excellence in science policy in the context of the enormous quantities of scientific outputs makes it imperative to screen out the most successful or influential work. "Many countries are moving towards research policies that emphasize excellence; consequently; they develop evaluation systems to identify universities, research groups, and researchers that can be

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said to be "excellent" [2]. Second, for visibility issues, academic professionals are consistently interested in pursuing high citations for their own work and also tend to follow the research with higher citations. In this way, they can stay current regarding research trends and make informed decisions on potential research topics. High citations imply more visibility, generally accompanied by more supports from public or private funders. Therefore, scientific researchers will be very much proud if their publications are selected as highly cited papers (HCPs).

Incites Essential Science Indicators (ESI), an analytic tool provided by Clarivate Analytics for identifying the top-charting research in Web of Science (WoS)-indexed journals, is widely used to evaluate HCPs, providing information such as the countries/regions [3, 4], institutes [5], and researchers [6], etc. ESI-HCPs, representing the top 1% in each of the 22 ESI subject fields, vary by fields and by years in a 10 years' rolling. A paper is selected as a HCP only if its citation count exceeds the 1% citation threshold of the corresponding research fields and publication year.

Over recent years, a number of studies have been conducted on HCPs based on data from ESI [7–9]. For example, Ioannidis Boyack et al. surveyed the most-cited authors of biomedical research for their views on their own influential published work [9]. Aksnes found that HCPs are typically authored by a large number of scientists, often involving international collaboration [10]. Some studies even try to predict the HCPs by mathematical models [11], implying "the first mover advantage in scientific publication" [12, 13]. That is, the first papers in a field will, essentially regardless of content, receive citations at a rate enormously higher than papers published later.

Bibliometrics, a term coined by Pritchard A [14], is a statistical method used to evaluate scientific development, determine research impacts, compare research performance and identify emerging fronts [15, 16]. There have been many bibliometric studies on natural science or social science as a general field [17, 18]. There have also been a few subject-specific ones on computer science [19, 20], on applied linguistics [21], and on operations research and management Science [22]. In this regard, bibliometrics has been applied to summarize the development of a specific subject, generating valuable information such as the most cited publications/journals and the most frequently explored topics, etc. Such information is of great importance and interest to researchers as well as academic institutions and government/private agencies in making funding and science policy decisions. However, to our knowledge, there has not been one bibliometric study on the specific subject "*Radiology, Nuclear Medicine & Medical Imaging*" *(RNMI)*, a subject that covers resources on radiation research in biology and biophysics. Of the five broad research areas (*Arts & Humanities, Life Sciences & Biomedicine, Physical Sciences, Social Sciences, technology*) in Web of Science database, *Life Sciences & Biomedicine* has the most number of subject categorizations (76 in total), implying the complexity and richness as well as importance of this research line. As an important subject area in *Life Sciences & Biomedicin*e in response to the rapidly evolving healthcare industry, the research productivity in this RNMI has been tremendous. A thorough investigation of the existing literature especially the HCPs will help keep researchers informed about the state of the arts and research trends in this subject.

The purpose of this study is to spotlight the trends and hot topics in the subject category of *Radiology, Nuclear Medicine & Medical Imaging* with the bibliometric analysis of highly cited papers to help researchers get the most updated information in the future study.

Materials and methods

A bibliometric approach was used in the present study to map the HCPs in RNMI in WoS. As one of the biggest bibliometric databases, WoS is the most frequently used database in bibliometric studies [23]. The methods for data retrieval are described as follows.

We searched in WoS Core Collection at the portal of the University library. We filtered the results by clicking the "*Highly Cited in Field*" trophy icon. We then downloaded all the bibliometric data for further analysis including publication years, authors and affiliations, publication titles, countries/regions, organizations, abstracts, citation reports, etc. After the removal of the publications with incomplete bibliometric information, a total of 1325 HCPs were harvested. The yearly publication distributions of the 1325 HCPs were shown in Figure S1 (Online Resource 1). The data retrieval was completed on 15 December, 2021. We collected the impact factor (IF) of each journal from the 2021 Journal Citation Reports (JCR).Table 1 shows the strategies of the retrieval queries.

Three points are to be mentioned here. First, the WoS Core Collection was searched because it boasts as an important bibliometric database which includes literature and citation information indexed in SCIE, SSCI and A&HCI. More importantly, it has been widely used in bibliometric analysis of previous studies both in natural sciences [24, 25] and

Table 1 Retrieval strategies

(from Web of Science Core Collection)
(Web of Science Categories = Radiology, Nuclear Medicine & Medical Imaging
Index: Science Citation Index Expanded (SCI-EXPANDED)
Refined by: Highly Cited Papers AND Language = English

in social sciences [21, 26]. Because RNMI belongs to the natural sciences, we restrict the index in SCI-expanded to retrieve the relevant data. Second, only articles and reviews are considered in HCPs selection. There is no need to restrict the document types in our search. Third, the dataset of ESI-HCPs is automatically updated every 2 months to include the most recent 10 years of publications. Therefore, only the papers in the recent decade will be counted as HCPs. There is no need to set the date range.

To identify the most influential papers, we ranked all the HCPs by the Relative Citation Rate (RCR), a new metric that uses citation rates to measure influence at the paper level [27]. Since the citation count a paper receives is closely associated with the number of years it is published, it is invalid to rank paper impact solely on Raw Citations (RC). Therefore, RCR, recently endorsed by the National Institutes of Health, has been employed here to pinpoint the most highly cited papers. RCR is based on weighting the number of citations a paper receives to a comparison group within the same field [28]. The *icite tool* is used here to generate RCR metrics for all the HCPs (https://icite.od.nih.gov/).

Word frequency analysis based on corpus is a bibliometric method to identify hotspots and developmental trend of one domain. In this study, we built an Abstract corpus with all the abstracts of the HCPs. The *n*-grams (2–4) in the corpus were retrieved and analyzed to detect the most frequently researched topics in the HCPs. The procedures to retrieve the n-grams were described as follows. First, the abstracts of all the 1325 HCPs from the downloaded bibliometric data were saved in separate files in txt. Formats in one folder to create a mini abstract corpus with a total of 299,810 tokens. Second, Anthony's AntConc, a freeware corpus analysis toolkit for concordancing and text analysis, was used to extract n-grams that include clusters of two to four continuous words [29]. AntConc is widely used in previous studies [16, 21, 26]. It automatically ranks all the retrieved n-grams in decreasing order. We also generated a list of individual nouns in case of missing some important topics. The reason to exclude the pronouns, modals and many other functional words is that research topics are usually phrases that do not contain these functional words. For topic candidacy, we adopt both frequency (10) and range criteria (10). That is, a candidate n-gram has to appear at least ten times and in at least ten different abstracts for further consideration. The frequency threshold ensures the significance of the candidate topics while the range threshold ensures the topics are not overly clustered in a limited number of papers. In this process, we actually tested the frequency and range thresholds several rounds for the inclusion of all the potential topics. In total, we got 521 nouns, 205 2 g, 39 3 g, and 5 4 g. Third, concerning the list of n-grams and monograms (nouns here), the authors discussed extensively to decide which should be taken as the potential research topics until full agreements were reached.

Besides the word frequency analysis based on the Abstract corpus, we performed knowledge mapping (i.e., network analysis) using VOSviewer (www.vosviewer.com), in which we focused on the network and "link strength" between author keywords. Knowledge mapping can be employed to map the scope and structure of the discipline while revealing key research clusters [30]. Since fractional counting approach assigns co-authored publications fractionally to each author, proper field-normalized results can be obtained [31]. Therefore, we used fractional counting in our analysis. This process produced the co-occurrence network of the most frequently used author keywords. Knowledge mapping of the author keywords was an important addition to the corpus based investigation of the abstracts.

Results

Main publication venues of HCPs

The top 20 journals with more than 17 HCPs published are listed in Table 2. They contributed around 80% of the total HCPs (1039/1325). The highest contribution comes from *Neuroimage (207)*, followed by *Radiology (159)*. They are also the only 2 journals with more than 100 HCPs, accounting for almost 30% of the total number of the HCPs, overwhelmingly exceeding the others on the list. As the only Q2 journal (between top 50% and top 25%) among the top five (the other four in the Q1, top 25%) by the Journal Citation Reports (JCR) quantile rankings, *Neuroimage* tops the list with certain surprise.

Because the total number of papers published in each journal varies greatly per year and the HCPs are also connected with journal circulations, we divide the total number of papers (TP) in the examined years (2011–2021) with the number of the HCPs to acquire the HCP percentage for each journal (HCPs/TP). As we can see, the top six journals with the highest percentage of the HCPs are *Med Image Anal (2.91), IEEE T Med Imaging (2.83)*, *Radiology (2.67)*, *Neuroimage (1.91)*, *J Cardiovasc Magn Reson (1.91), JACC-Cardiovasc Imag (1.75).* That implies that papers published in these journals have a higher probability to enter the HCPs list. In terms of the latest journal impact factor (IF) in 2021, the top five journals with the highest IF are *JACC-Cardiovasc Imag* (14.805), *Radiology* (11.105), *J Nucl Med* (10.057), *IEEE T Med Imaging* (10.048) and *Eur J Nucl Med Mol I (9.236)*. The number of the HCPs in these journals take up a large share of the total HCPs (over 30%), implying a close relationship between the journal IF and the number of the HCPs in the journal.

Table 2 Main publication venues of the HCPs ranking in decreasing order

	JCR Abbreviated title	HCPs	TP	HCPs/TP (%)	HCPs/1325(%)	IF (2021)
1	Neuroimage	207	10,814	1.91	15.623	6.556
2	Radiology	159	5959	2.67	12	11.105
3	IEEE T Med Imaging	74	2613	2.83	5.585	10.048
4	J Nucl Med	68	21,049	0.32	5.132	10.057
5	JACC-Cardiovasc Imag	58	3305	1.75	4.377	14.805
6	Eur Radiol	54	6440	0.84	4.075	5.315
7	Eur J Nucl Med Mol I	49	21,158	0.23	3.698	9.236
8	IJROBP	46	33,071	0.14	3.472	7.038
9	Med Image Anal	46	1580	2.91	3.472	8.545
10	Radiother Oncol	46	23,107	0.2	3.472	6.28
11	Ultrasound Obst Gyn	32	3287	0.98	2.415	7.299
12	Am J Roentgenol	29	7210	0.4	2.189	3.959
13	Magn Reson Med	29	5261	0.56	2.189	4.668
14	Am J Neuroradiol	24	4586	0.52	1.811	3.825
15	Eur Heart J-Card Img	23	3144	0.73	1.736	6.875
16	J Magn Reson Imaging	21	4440	0.48	1.585	4.813
17	J Cardiovasc Magn Reson	20	1049	1.91	1.509	5.364
18	Med Phys	20	32,893	0.06	1.509	4.071
19	Circ-Cardiovasc Imag	17	1855	0.91	1.283	7.792
20	KJR	17	1548	1.1	1.283	3.5

Countries distribution

The top 16 productive countries with more than 50 HCPs are presented in Fig. 1. The USA took the lead with 707 HCPs (53.358%), confirming its leading position as a traditional scientific powerhouse in this subject, followed by Germany (20.302%) and England (19.623%). It is to be mentioned that only three Asian countries enter the top 16 list (*China, South Korea, Japan*). *China* even boasts the fourth position with 196 HCPs (14.792%). However, scholars from outside the traditional publishing countries need to be more visible for their work in RNMI.

Most influential papers by RCR

During the data processing, we found that the papers on COVID-19 published in the year of 2020 had extremely high RCR compared to papers on other subjects. As an

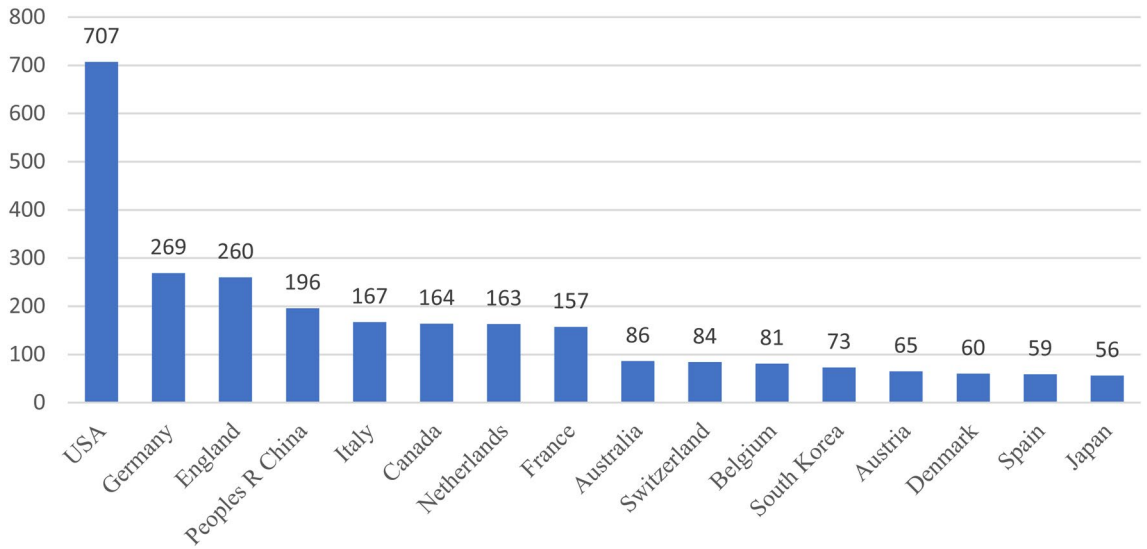

Fig. 1 Top 16 countries/regions with the most HCPs

unexpected global epidemic starting in late 2019, COVID-19 ignited research interests from all over the world especially in China where the epidemic was first reported. Many papers got quickly published and cited during this period in response to the urgent needs to find treatments. If we mix the papers, paying no attention to this public health incident, the COVID-19-related papers will take up 75% of the top 20 highly cited papers in terms of RCR (15/20), which was unfair for other non-COVID-19-related papers because of the distorted impact image. Therefore, we produced two lists of ranking: one for the non-COVID-19 papers in Table 3 and one for the COVID-19 papers in Table 4. The yearly citation trends of each listed HCP can be seen in Figure S2 (Online Resource 2).

Table 3 The Top 20 HCPs (Non-COVID-19)

	Year	Title	Journal	Type	RC	RCR	PMID
1	2015	Recommendations for cardiac chamber quantification…	Eur Heart J Cardiovasc Imaging	R	3028	203.92	25,712,077
2	2012	FSL	Neuroimage	R	4264	195.46	21,979,382
3	2012	Spurious but systematic correlations in…	Neuroimage	A	3960	178.77	22,019,881
4	2017	A survey on deep learning…	Med Image Anal	R	1575	159.99	28,778,026
5	2016	Radiomics: Images Are More than …	Radiology	A	2018	154.28	26,579,733
6	2016	Recommendations for the Evaluation of …	J Am Soc Echocardiogr	R	1701	132.96	27,037,982
7	2012	FreeSurfer	Neuroimage	R	2461	109.24	22,248,573
8	2020	The Image Biomarker Standardization Initiative…	Radiology	A	274	95.4	32,154,773
9	2012	3D Slicer as an image …	Magn Reson Imaging	A	1839	91.22	22,770,690
10	2014	Permutation inference for the general…	Neuroimage	A	1467	79.27	24,530,839
11	2012	ESUR prostate MR guidelines 2012	Eur Radiol	R	1501	74.85	22,322,308
12	2016	An integrated approach to correction…	Neuroimage	A	924	71.48	26,481,672
13	2014	Methods to detect, characterize, and remove…	Neuroimage	A	1331	71.39	23,994,314
14	2013	The WU-Minn Human Connectome Project…	Neuroimage	R	1533	70.94	23,684,880
15	2012	The influence of head motion…	Neuroimage	A	1568	68.83	21,810,475
16	2015	FDG PET/CT: EANM procedure guidelines…	Eur J Nucl Med Mol Imaging	R	1032	67.64	25,452,219
17	2013	The minimal preprocessing pipelines for…	Neuroimage	A	1422	66.9	23,668,970
18	2017	Guidelines for Management of Incidental…	Radiology	R	699	65.32	28,240,562
19	2015	Recommended implementation of arterial spin-labeled …	Magn Reson Med	R	931	62.88	24,715,426
20	2013	Optical properties of biological tissues…	Phys Med Biol	R	1151	60.97	23,666,068

Note: To save space, not full information about the HCPs is given. For the source title, only the first five words were kept if the titles are too lengthy. PMID are provided to locate the papers quickly for those interested. For the authors, only the first author who appeared in the author list was given. For the document type, *R* means Reviews while *A* means Articles

Table 4 The top 10 HCPs (COVID-19)

	Year	Title	Journal	Type	RC	RCR	PMID
1	2020	Correlation of Chest CT and…	Radiology	A	1954	703.55	32,101,510
2	2020	Sensitivity of Chest CT for…	Radiology	A	1052	378.05	32,073,353
3	2020	Time Course of Lung Changes…	Radiology	A	990	354.05	32,053,470
4	2020	CT Imaging Features of 2019…	Radiology	A	941	332.85	32,017,661
5	2020	Chest CT Findings in Coronavirus…	Radiology	A	896	320.15	32,077,789
6	2020	Chest CT for Typical Coronavirus…	Radiology	A	775	272.91	32,049,601
7	2020	Coronavirus Disease 2019 (COVID-19)…	Radiology	R	486	180.92	32,083,985
8	2020	Emerging 2019 Novel Coronavirus…	Radiology	A	499	177.52	32,027,573
9	2020	Coronavirus Disease 2019 (COVID-19)…	Am J Roentgenol	R	493	174.47	32,174,129
10	2020	Frequency and Distribution of Chest…	Radiology	A	455	168	32,216,717

Note: To save space, not full information about the HCPs is given. For the source title, only the first five words were kept if the titles are too lengthy. PMID are provided to locate the papers quickly for those interested. For the authors, only the first author who appeared in the author list was given. For the document type, *R* means Reviews while *A* means Articles

Table 3 shows some interesting patterns. First, 9 out of the top 20 HCPs were published in *Neuroimage*, which helps corroborate the findings on the main publication venues. Second, in terms of the document types, reviews (11) slightly outnumber articles (9), which may imply that reviews share the same amount of citation opportunities as the articles in the field of medical studies if not more. Third, three types of research orientations can be discerned from the top 20 HCPs: recommendations or guidelines (#1, 6, 11, 16, 18, 19); processing software (#2, 7, 9); analysis methods (#4, 5, 8, 12, 13, 15, 17, etc.).

The top ten highly cited papers on COVID-19 shows a different picture in Table 4. 9 out of the top ten HCPs were published in *Radiology*, which once again testifies its popularity and importance in the field of *RNMI*. *Ai tao*'s (2020) *Correlation of Chest CT and* …tops the list with RCR at 703.55, three times more than *Roberto M Lang* (2015) with RCR at 203.92, which shows the enormous attention paid to this unprecedented epidemic outbreak.

Most frequently explored topics

Table 5 presents the top 33 research topics above the observed frequency of 38. The observed frequency count for each topic in the abstract corpus is included in the brackets. Topics such as *magnetic resonance imaging (325), deep learning (191), prostate cancer (162), chest CT (145), computed tomography (141), CT images (121), PSMA PET (119), coronavirus disease (115), convolutional neural network(s) (108)* and *FDG PET (100)* were the top ten most frequently mentioned topics based on the corpus analysis of the abstracts. We grouped the topics into five broad categories, including devices, organs, artificial intelligence (AI), images, and others, according to topic relationships.

The first group is mainly about the imaging devices in the RNMI field including *MRI (396)*, *CT* (484) and *PET (279)*.

The second group concerns the human organs such as *brains (250), prostate (162), heart (160), lungs (153), and breast (93)*. Cancer-related phrases (prostate cancer, and breast cancer) were among the top list in frequency. For the brain, topics such as *functional connectivity and white matter* were more mentioned.

The third group are all related to AI technology (*artificial intelligence, deep learning, machine learning, convolutional neural networks,* etc.).

The fourth group is about image information. *Image quality* is an important focus in MR/CT/PET scanning because it determines whether the images can been used or not. *Imaging features* can provide more information and are widely used in AI.

Topics in the last group constitute the core concepts in radiology. *Radiation therapy* is the most important treatment method for cancers. Especially when combined with MRI and CT, precise radiotherapy will be a promising alternative for cancer treatment in the future. As the method for assessing diagnosis performance of quantitative parameters, *receiver operating characteristic* (ROC) is also the main technology. *Contrast agents* is the important part of CT and MRI scans. *Polymerase chain reaction* is the gold standard in the detection COVID-19. It is no wonder that these topics enter the hot topic list because they are closely connected to the topics in other categories.

Author keywords analysis

A total of 2796 keywords were retrieved. We set the minimum number of occurrences of a keyword at 5. Then, 131 keywords meet the threshold. For each of the 131 keywords, the total strength of the co-occurrence links with other keywords were calculated. The top 15 keywords with the greatest total link strength were shown in decreasing order in Table 6. VOSviewer classified the 131 keywords

Table 5 Categorization of the most explored research topics

Topic categorization	Topic items
Devices (1159)	MRI (396): magnetic resonance imaging (325); MR images (71)
	CT (484): chest CT (145), computed tomography (141), CT images (121), CT scans (77)
	PET (279): PSMA PET (119), FDG PET (100), PET CT(60)
Human Organs (818)	Brain (250): functional connectivity (85), white matter (77), human brain (50), brain regions (38);
	Prostate (162): prostate cancer (162);
	Heart (160): left ventricular (57), cardiology foundation (54), heart failure (49);
	Lung (153): coronavirus disease (115), respiratory syndrome (38);
	Breast (93): breast cancer (93)
AI (495)	Deep learning (191), convolutional neural network(s) (108), machine learning (79), neural networks (71), artificial intelligence (46)
Images (201)	Image quality (70), imaging features (51), signal intensity (40), image analysis (40)
Others (248)	Radiation therapy (88), receiver operating characteristic (73), contrast agents (48), polymerase chain reaction (39)

Table 6 The top keywords in HCPs

	Keyword	Occurrences	Total link strength
1	Deep learning	99	79
2	COVID-19	80	74
3	MRI	52	42
4	Machine learning	44	40
5	Prostate cancer	47	39
6	Computed tomography	41	39
7	Pneumonia	37	36
8	Magnetic resonance imaging	43	31
9	PET	34	30
10	fMRI	38	30
11	PET/CT	32	28
12	PSMA	27	26
13	CT	26	24
14	Sars-cov-2	23	23
15	Radiomics	21	21

into 9 clusters, as shown in Fig. 2. The link strengths for *deep learning, covid-19, mri, machine learning, prostate cancer, computed tomography* were 79, 74, 42, 40, 39, 39, respectively. The thickness of the lines which was determined by the frequency of the keywords in HCPs shows the link strength between the keywords.

A comparison between the word frequency analysis of the Abstract corpus and the knowledge mapping of the author keywords shows similar research activities, which can be evidenced by the overlapping of the high frequent topics and the author keywords. These hot terms not only reflects the important research trends up to now, but also points the direction for future research in RNMI. For example, AI is gaining increasing popularity in the healthcare industry especially in handling a huge amount of patient data and recognizing complex disease patterns. In the future, AI-based technology is bound to unfold more hidden information from big data and inform healthcare policymakers and clinicians in making effective clinical decisions. Besides, considering the complex functioning of the human brain, the research is multidisciplinary in nature. Therefore, a collaboration across scientific disciplines will better reveal the intricacies of the human brains.

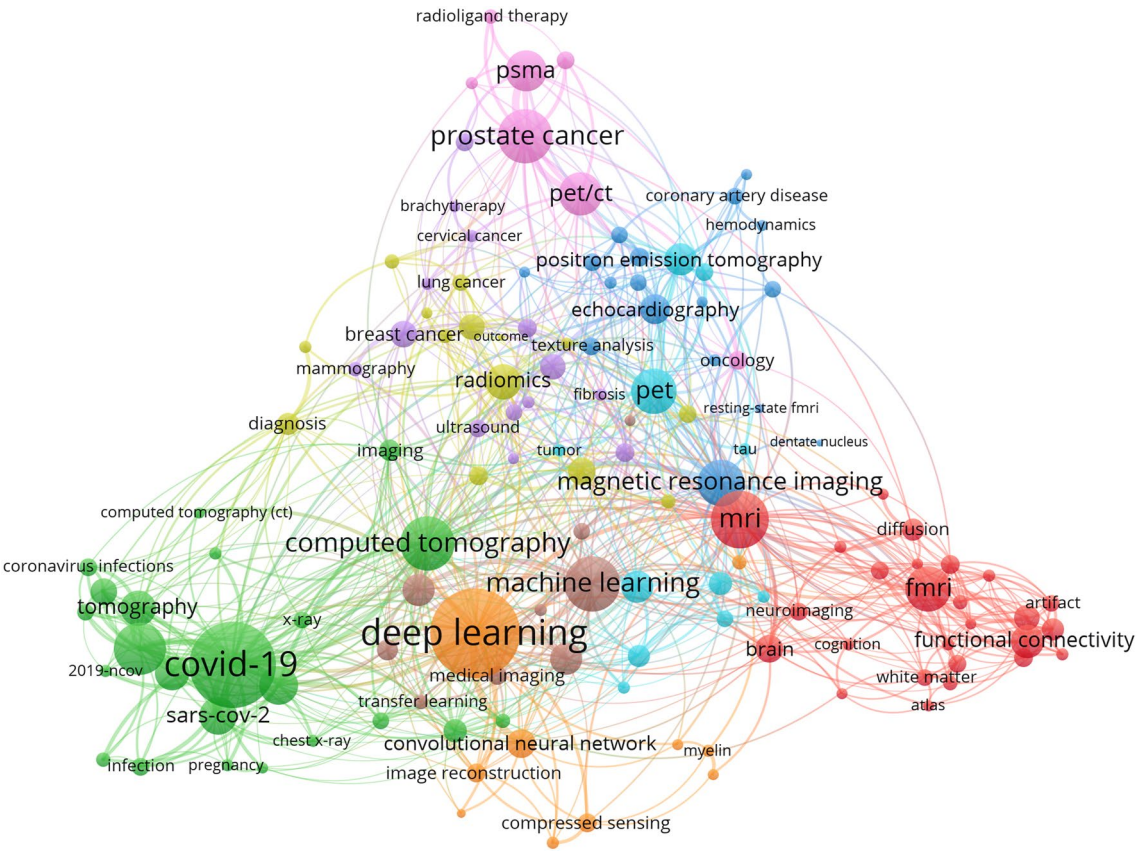

Fig. 2 The co-occurrence of author's keywords

Discussion

To our knowledge, this is the first comprehensive bibliometric study of Highly Cited Papers (HCPs) in the subject category of RNMI across the years spanning from 2011 to 2021. The results showed that *Neuroimage, Radiology, IEEE T Med Imaging, J Nucl Med* had the largest number of HCPs published, accounting for about 40% of the total 1325 HCPs. The traditional academic powerhouses in RNMI such as the USA, Germany and England are leading the publications while countries such as China and Italy are catching up. For the top 20 non-COVID-19 HCPs, 3 types of research orientations can be detected: *recommendations or guidelines; processing soft wares; analysis methods*. Reviews slightly outnumber articles in terms of document types. Among the top ten COVID-19 HCPs published in the year 2020, nine were published in *Radiology,* and *chest CT* was the most frequent used term in the paper titles.

It is interesting to find *Neuroimage,* the only Q2 journal in the top five, tops the list with the most HCPs. Research on human brains is increasing rapidly since the initiation of the WU-Minn Human Connectome Project in America in September 2010, aiming to map macroscopic human brain circuits and their relationship to behavior[32]. Many countries/regions follow the lead by starting their own brain projects, such as *Human Brain Project* in European Union, *Brain/Minds* in Japan, and *Brain Science and Brain-Like Intelligence Technology* in China. Therefore, topics such as *functional connectivity, white matter, brain regions* can be found (Table 5), reflecting the scientific enthusiasm in human brains. The surging research interest in brain functioning in the last decade across the globe stimulated more papers in related journals such as *Neuroimage*, especially after the initiation of the WU-Minn Human Connectome Project in September 2010. Besides, from January 2020, *Neuroimage* is an open access journal. Authors who publish in *Neuroimage* can make their work visible immediately, which might encourage more authors to contribute their work. It can be evidenced by more publications in *Neuroimage* in 2020 compared to those in previous years.

United States, Germany and England are undoubtedly the most impactful in the research area of RNMI. Historically, western countries, especially the United States, have been at the center of academic publishing, supported by huge investments in scholarly research and technical infrastructure. Besides, because the research in RNMI usually involves highly priced facilities such as MRI scanner, the developed countries with more resources clearly stand in a more advantageous position in research and publishing. It should be noted here that a HCP is usually the joint writing of multiple authors from different institutions and/or countries[10]. Web of Science will generate all the bibliometric information of the papers, not restricted to the information about the first author or the corresponding author. In other words, all the countries and institutions listed on the HCPs will be treated evenly. In this way, a clearer picture about the HCPs distribution across countries can be painted.

Scientific research has always been driven by practical needs. It comes with no surprise that *Roberto M Lang*'s (2015) *Recommendations for cardiac chamber quantification*[33]…tops the list with RCR at 203.92. The quantification of cardiac chamber size and function is the cornerstone of cardiac imaging. Jointly written by the *American Society of Echo cardiography and the European Association of Cardiovascular Imaging*, *Roberto M Lang*'s (2015) is the updated recommendations for cardiac chamber quantification that guide the echo cardiographic practice with sweeping popularity. Because COVID-19 was first reported in China, most of the studies during this period were conducted in hospitals or universities in China, which can be easily seen from the top ten HCPs list. *Sana Salehi's (2020) Coronavirus Disease 2019 (COVID-19)…*stands as the only HCP among the top ten beyond China (in USA). From the titles, Chest CT emerges as one of the hottest phrases. The fact that most patients infected with COVID-19 had pneumonia and characteristic CT imaging patterns helps explain its frequent use.

A great overlap between the most frequently explored topics and author keywords is identified. The hot topics can be generally grouped into five broad categories: *devices, organs, artificial intelligence (AI), images, and others*. *MRI* is the most frequently mentioned phrase. Compared to CT which only shows signal attenuation and has ionizing radiation, MRI can obtain the multi-contract images without ionizing radiation, and is widely used in whole human bodies except the lung. Especially, in the human brain projects, MRI is the main device. However, CT showed greater values in the lung disease than MRI, which can be evidenced by frequent use of CT in the COVID-19 publications. The use of *PET* (positron emission tomography) scan along with CT in clinical practice increases side by side with publications in this regard which can be seen in such frequent topics as *PET CT, PSMA PET, FDG PET*. Moreover, the clinical value of PET with MR is also increasing proven. In the future, PET will be an important device in the field of nuclear medicine and radiology.

Besides brain, lung, prostate, heart, and breast are the most concerned organ. According to the World Health Statistics released in 2020, an estimated 41 million people worldwide died of NCDs (noncommunicable diseases) in 2016, equivalent to 71% of all deaths. Four NCDs caused most of those deaths: cardiovascular diseases (17.9 million deaths), cancer (9.0 million deaths), and chronic respiratory

diseases (3.8 million deaths), and diabetes (1.6 million deaths) (*World health statistics 2020: monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization; 2020.*). Of different cancer types, breast cancer, lung cancer, and prostate cancer were the top three most prevalent cancers, according to the latest GLOBOCAN2020 report by the International Agency of Research on Cancer, part of World Health Organization.

In recent years, AI has been a hot theme of modern technology and is creeping into almost every facet of modern life including medical research. Up to now, AI has been actively used in medical images recognition, medical intelligent decision-making, medical intelligent voice, and "Internet plus" medical treatment. As one of the first specialty in healthcare to adopt digital technology, radiology is well positioned to deploy AI for diagnostics due to digital images [34]. Gulshan first reported that AI could automated detected diabetic retinopathy and diabetic macular edema from over 100 thousand retinal fundus photographs, with high sensitivity and specificity [35]. In 2017, Golden reported that AI can quickly read photos to diagnose breast cancer with lymph mode metastases, greatly improving the speed of diagnosis [36]. AI also played an important role in detecting COVID-19 [37–39]. In the future, AI is bound to exert greater influence on the medical field. For example, AI shows great promise in changing treatment models, promoting medicine development, reshaping the medical industry, and even impacting the career paths of the medical practitioners. It is believed that *artificial intelligence* will bring profound changes to future medical technology and will be a powerful driving force for future medical innovation and reform.

There are several points to be mentioned here as for the most frequently explored topics. Decisions regarding the candidate topics were not easy and involved subjectivity. It was the results of several rounds of discussions from multiple professionals. Some n-grams are discarded because they are too general or not meaningful topics in RNMI. For example, quantitative analysis, high sensitivity, imaging technique and medical image are too general to be included. By meaningful topics, we mean the n-grams can help journal editors and readers to quickly locate their interested fields, as the author keywords such as brain networks, MRI imaging, CT scans. Besides, the examination of the limited 3/4-g and monograms (nouns) revealed that most of them were either not meaningful topics such as cancer detection rate and patients with prostate cancer or they were topics already identified in the 2 g such as weighted MR imaging in MR imaging. Therefore, the final list is mostly 2-g topics.

It should be noted that large numbers of quantitative data have been used here to map the HCPs from different perspectives. Despite the quantitative nature, our study also involves qualitative analysis and hence subjectivity, especially concerning what constitutes the research topics and topic categorization. Given the rapid developments in RNMI, more bibliometric research is needed in the future to help test and enhance the validity and reliability of this research approach and to help keep us accurately informed about the trends in RNMI.

Our study also has some limitations. The subject category of Radiology, Nuclear Medicine & Medical Imaging listed in WoS Categories needs to be further broken down into subcategories and subjects in future analysis. A finer granular subject classification of the research area would have painted a more detailed picture. In additional, the study focuses on the apex of the publishing pyramid in RNMI, the HCPs. And the bibliometric indexes here are all based on the WoS SCI international journals. Although these are the most celebrated and accessible works, some other publications of similar importance or highly localized publications which do not have the chance to enter the list and are not indexed in WoS are not given due attention in our study. This less widely cited research is a rich vein for future study. At last, the study seems to show that the number of citations a review paper receives is higher than that of an original article in RNMI. Therefore, it might be more useful to distinguish the two types of papers in future method design.

In conclusion, our results of the bibliometric analysis provided the updated trends and hot topics in RNMI. And the practitioners and researchers in RNMI can be better aided to locate the relevant literature and keep informed about the hot topics.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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