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Review

Bibliometric Analysis on the Trend of the Computed Tomography (CT)-Related Studies in the Field of Forensic Science

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Abstract: The computed tomography (CT) technique has attracted much attention as a promising tool for non-invasive diagnosis and examination in the field of forensic science. The purpose of this study is to assess the trend in CT-related forensic studies through bibliometric methods and thus present a holistic idea about the application of CT in the field of forensic science of the past and present. A total of 2084 articles published in the Scopus index journals between 1978 and 2020 were analyzed using VOSviewer 1.6.15. A drastic increase in the number of CT-related articles was noticed in forensic science since the early 2000s. Switzerland, having the most productive institution (University of Zurich) and author (Michael J. Thali), contributed most to the increasing number of publications. *Forensic Science International* was the top journal, where approximately 12.5% of the articles (261 out of 2084) have been published. CT was frequently used for autopsy and diagnosis purposes, but recently its applicability has expanded to the field of forensic anthropology and personal identification. This research is expected to provide researchers using CT with not only an understanding about past research trends but also an insight about future research topics and potential collaborative opportunities.

Keywords: bibliometric analysis; computed tomography; forensic science; Scopus; VOSviewer

1. Introduction

There has long been an effort to devise non-invasive diagnostic techniques in the fields of medical and forensic sciences. The radiographs introduced by Conrad Roentgen in 1895 have opened the era of forensic radiology since the first postmortem radiographic examination in 1898 [1]. With the development of three-dimensional imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) in the late 20th century, forensic imaging has attracted much attention as a new non-invasive diagnostic tool as well as a new subfield of forensic science [2,3]. Compared to the radiographs, forensic imaging using cross-sectional techniques has advantages in that it allows for three-dimensional examination and visualization of complex structures in an easy and interactive way [1,4]. Indeed, the past two decades have seen a drastic development of CT techniques and subsequently a rapid growth in the application of CT in the forensic context [5].

The purpose of this study is to quantitatively assess the trend of CT-related forensic studies through bibliometric methods and thus present a holistic idea about the application of CT in the field of forensic science of the past and present. Bibliometric studies allow to track the frequencies and trends of scientific publications associated with a specific field/topic and the relationship of citations

between the works in a systematic way [6,7]. Specific focus will be placed on the growth trend of this field in terms of the number of publications, most active journals with trend topics, and productive authors and countries. This research is expected to provide researchers using CT with not only an understanding about the past research trend but also an insight about future research topics and potential collaborative partners.

2. Materials and Methods

The Scopus indexed articles were searched using the *Document Search* function [8] on 4 November 2020. Four terms—"forensic" OR "medicolegal" OR "legal medicine" AND "computed tomography"—were used for document search so that any articles containing one of the three pairs of keywords (i.e., "forensic—computed tomography", "medicolegal—computed tomography", or "legal medicine—computed tomography") in their title, abstract, and/or keywords could be detected. Document type was limited to "Articles and Reviews" so other types of publications such as book chapters, letters, conference papers, and surveys were excluded. The years of publication were not specified, and Ostertag et al.'s [9] work titled "Diagnostic possibilities of computerized tomography in forensic examination of cerebral traumatized persons" was marked as the earliest article. The citation information (e.g., authors, title, publication year, citation counts, and source), bibliographic information (e.g., affiliations and correspondence address), abstract and keywords, and reference information of all selected articles were exported in a comma-separated values (CSV) file format for further analyses. Informed consent was not required from the authors of the articles because the data were collected as secondary data lacking personal information.

Microsoft Excel was used to calculate descriptive statistics and annual growth rate (AGR) and to produce related plots. AGRs were calculated as follows, which represents the percentage rate of positive or negative growth of a product in a certain year compared to the previous year [10].

$$AGR_i = \frac{N_i - N_{i-1}}{N_{i-1}} \times 100$$

where N_i: number of documents in the year i.

In calculating AGRs, only the articles published between 2000 and 2019 were included, during which drastic increase in publications was observed. The publications in 2020 were excluded from the AGR calculation because the number of publications at the time of data collection for this study could not represent that of the entire year.

VOSviewer 1.6.15 [11] was used for bibliometric analysis. VOSviewer is an open source computer program which makes it possible to perform bibliometric analyses and display two-dimensional maps based on the co-occurrences of the nodes/subjects [12]. One of the advantages of using VOSviewer for this purpose is that VOSviewer can analyze the bibliometric data exported from the major journal archives such as Scopus, Web of Science, and PubMed directly.

3. Results

3.1. Annual Trend of Publications

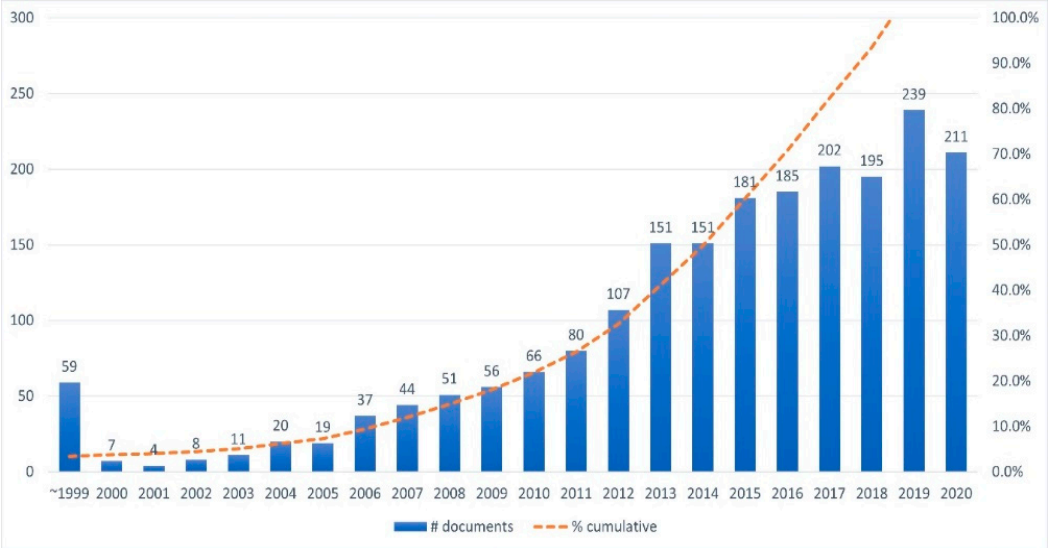
Per the ScopusS document search, a total of 2084 CT-related articles have been published in the forensic field since the 1970s (Table 1). The numbers of published articles per year were below ten until 2002 and the sum of publications between 1978 and 2002 constitutes only 3.7% of the total publications (78 out of 2084). However, from the early 2000s, a drastic increase in the number of publications is noticed (Table 1 and Figure 1a). Since 2001, each year set a new record in the number of annual publications except for 2005, 2014, and 2018. More than 100 articles have been published every year since 2012; and 2017 was the first year during which more than 200 articles were published. The first quartile (25%) in the number of publications was reached in 2012. Yet, it took only three years for the second and third quartiles to be reached (2015 and 2018, respectively). Figure 1b shows a fluctuating

trend in AGR. The AGR indicates a relative growth of publications within a year compared to the previous year. For example, a positive AGR indicates that the number of publications in a certain year exceeded that of the previous year, and vice versa. Since 2000, there were three years with negative ARG's (−42.9% in 2001, −5.0% in 2005, −3.5% in 2018) (Table 1 and Figure 1b). However, the differences in numbers of publications between those years and their preceding years were minimal (three in 2001–2000; one in 2005–2004; and seven in 2014–2013).

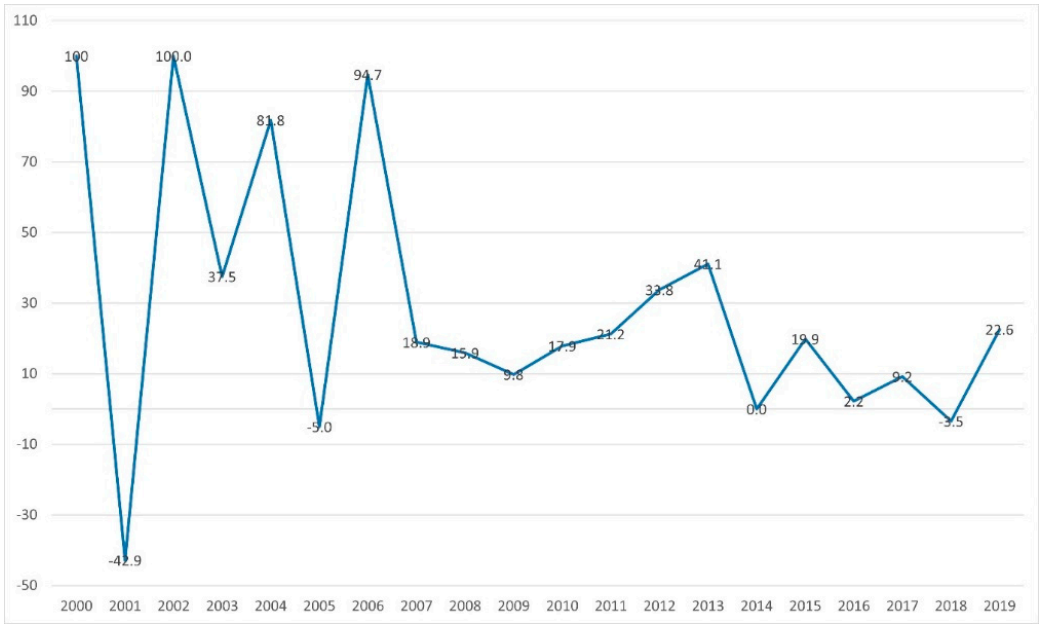
Table 1. The number and annual growth rate (AGR) of CT (computed tomography) -related articles in the Forensic section of Scopus between 1978 and 2020.

Publication Year *	Number of Documents	Cumulative Total	Annual Growth Rate (%) **
1978	1	1	
1980	1	2	
1981	1	3	
1982	3	6	
1983	1	7	
1985	8	15	
1986	4	19	
1988	1	20	
1989	1	21	
1990	1	22	
1992	2	24	
1993	2	26	
1994	6	32	
1995	5	37	
1996	6	43	
1997	6	49	
1998	7	56	
1999	3	59	
2000	7	66	100.0
2001	4	70	−42.9
2002	8	78	100.0
2003	11	89	37.5
2004	20	109	81.8
2005	19	128	−5.0
2006	37	165	94.7
2007	44	209	18.9
2008	51	260	15.9
2009	56	316	9.8
2010	66	382	17.9
2011	80	462	21.2
2012	107	569	33.8
2013	151	720	41.1
2014	151	871	0.0
2015	181	1052	19.9
2016	185	1237	2.2
2017	202	1439	9.2
2018	195	1634	−3.5
2019	239	1873	22.6
2020	211	2084	
Total	2084		

* Years with no publications are not presented; ** Only the AGRs between 2000 and 2019 are presented.



(**a**)



(**b**)

Figure 1. Number of annual publications (**a**) and annual growth rate (AGR) of the publications (**b**). The positive and negative values of AGR indicate that the number of publications within a year was greater or less than the previous year, respectively.

3.2. Productive Countries

CT-related forensic studies have been conducted by the authors from 104 countries. Table 2 and Figure 2 show top 16 countries that have produced 40 or more articles. Switzerland was the most productive country in terms of the number of publications (n = 335) as well as the number of citations (n = 6662) followed by United States (# articles = 259; # citations = 4775).

Table 2. Countries that have published 40 or more CT-related articles in the Forensic section of Scopus between 1978 and 2020.

Country	Number of Documents	Number of Citations
Switzerland	335	6662
United States	259	4775
Japan	224	2278
Germany	207	3534
United Kingdom	186	2719
Italy	173	2005
France	144	1625
Australia	106	1692
China	90	393
Turkey	79	686
India	71	381
Brazil	51	308
The Netherlands	47	396
Denmark	45	522
Malaysia	42	174
Egypt	40	253

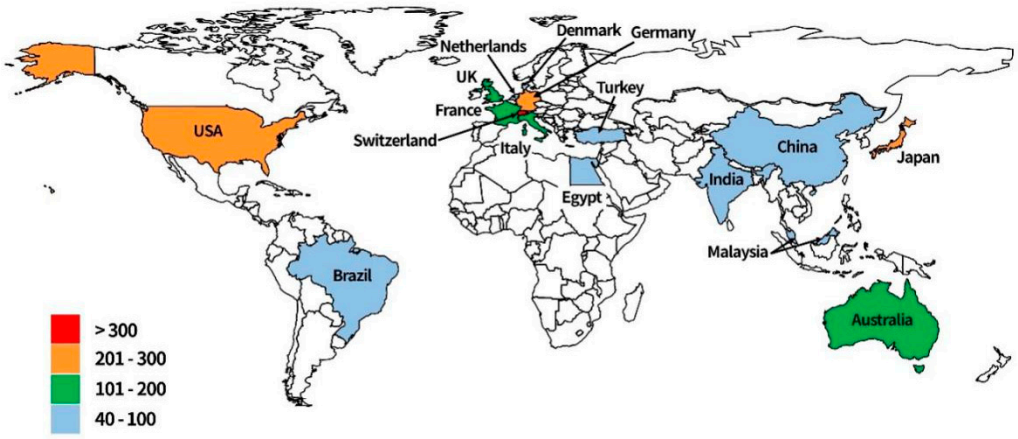


Figure 2. Color map showing the countries that have published 40 or more CT-related articles in the Forensic section of Scopus between 1978 and 2020.

The co-authorship analysis shows that Switzerland, the United States, the United Kingdom, Italy, and Germany were the top 5 countries in terms of the collaborative network (Figure 3). The size of the circles and thickness of the lines in Figure 3 indicate the total link strength of a country and the strength of network between two countries, respectively. Based on the strength and pattern of the network, four clusters could be found out of 16 countries: (i) Australia, Brazil, Denmark, The Netherlands, the United Kingdom, and the United States, (ii) Egypt, India, Japan, Malaysia, and Turkey, (iii) Germany, Italy, and Switzerland, and (iv) China and France.

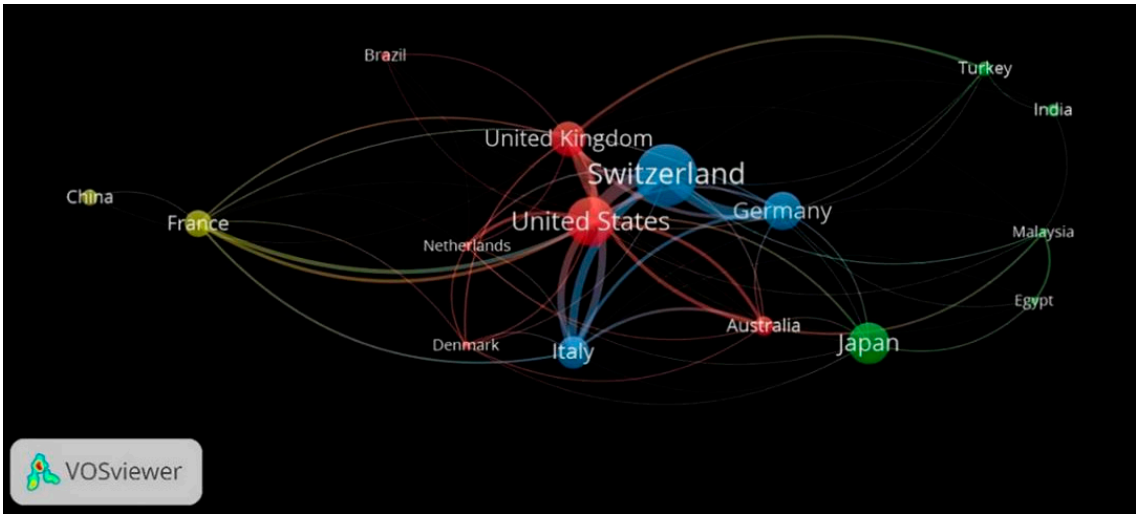


Figure 3. Network visualization map showing the collaborative relations among top 16 countries. The size of circles and fonts denotes the total link strength of the frequency of collaborations; the thickness of lines indicates the strength of collaborations between two countries; and the color indicates the clusters of collaborations.

3.3. Productive Institutions and Authors

A total of 5929 authors from 5194 institutions have contributed to CT-related forensic studies. Tables 3 and 4 list the authors and institutions that have published 30 or more articles. Among the 27 authors in Table 4, Michael J. Thali is the only one who authored more than 100 articles. Among the 16 institutions that produced 30 or more articles, six institutions are located in Switzerland; two in Australia, France, Japan, and the United Kingdom; and one in China and Germany. It was also noted that all the top three institutions—University of Zurich (# articles = 159), University of Bern (# articles = 136), and UniversitätsSpital Bern (# articles = 87)—are located in Switzerland.

Table 3. Authors who have published 30 or more CT-related articles in the Forensic section of Scopus between 1978 and 2020.

Author	Number of Occurrence	Number of Citations	Author	Number of Occurrence	Number of Citations
Thali M.J.	180	4453	Dirnhofer R.	43	2633
Iwase H.	61	631	Dedouit F.	41	599
Ampanozi G.	60	663	Motomura A.	41	356
Gascho D.	57	382	Rutty G.N.	41	933
Makino Y.	57	500	Thali M.	40	888
Jackowski C.	55	2364	Torimitsu S.	40	335
Schweitzer W.	53	770	Morgan B.	37	890
Flach P.M.	49	505	Bolliger S.A.	35	677
Telmon N.	49	698	Yen K.	33	1497
Grabherr S.	48	928	Aghayev E.	30	1404
Ruder T.D.	46	766	Hatch G.M.	30	498
Inokuchi G.	45	390	Ross S.	30	985
Yajima D.	44	530	Verhoff M.A.	30	444
Chiba F.	44	348			

Table 4. Institutions that have produced 30 or more CT-related articles in the Forensic section of Scopus between 1978 and 2020.

Institution	Number of Documents	Country
University of Zurich	159	Switzerland
University of Bern	136	Switzerland
UniversitätsSpital Bern	87	Switzerland
Chiba University	59	Japan
Victorian Institute of Forensic Medicine	50	Australia
University of Tokyo	46	Japan
Hopital de Rangueil	46	France
UniversitätsSpital Zurich	45	Switzerland
Monash University	44	Australia
Universitätsklinikum Hamburg-Eppendorf und Medizinische Fakultät	40	Germany
University of Leicester	40	United Kingdom
Leicester Royal Infirmary	39	United Kingdom
Université de Lausanne UNIL	38	Switzerland
Anthropologie Moléculaire et Imagerie de Synthèse	35	France
Centre Hospitalier Universitaire Vaudois	31	Switzerland
Ministry of Justice, China	31	China

3.4. Leading Journals

Out of 408 journals selected by the Scopus search, only 23 journals have published ten or more CT-related forensic studies (Table 5). *Forensic Science International* is ranked as the most active journal in terms of the number of publications (n = 261) as well as the number of citations (n = 5241), which is followed by the *International Journal of Legal Medicine* (# articles = 200; # citations = 3424).

Table 5. Journals that have published ten or more CT-related articles in the Forensic section of Scopus between 1978 and 2020.

Journal	Number of Documents	Number of Citations
Forensic Science International	261	5241
International Journal of Legal Medicine	200	3424
Journal of Forensic Radiology and Imaging	156	876
Journal of Forensic Sciences	146	2865
Legal Medicine	146	1430
Forensic Science, Medicine, and Pathology	98	1122
Journal of Forensic and Legal Medicine	65	621
American Journal of Forensic Medicine and Pathology	58	670
Rechtsmedizin	43	207
Indian Journal of Forensic Medicine and Toxicology	37	1
Journal of Forensic Medicine	30	24
Romanian Journal of Legal Medicine	29	55
Radiologia Medica	25	337
Australian Journal of Forensic Sciences	24	48
Forensic Imaging	24	10
Academic Forensic Pathology	19	32
Egyptian Journal of Forensic Sciences	15	80
European Radiology	12	620
Medicine, Science, and the Law	12	52
Plos One	12	78
Revue de Medecine Legale	12	9
American Journal of Physical Anthropology	10	142
Seminars in Ultrasound, CT, and MRI	10	83

Figure 4 displays the citation network among the top ten journals where 30 or more articles have been published. The size of the circles in Figure 4 denotes the total link strength (i.e., the relative frequency of a journal's citations by other journals). Obviously, the articles published in *Forensic Science International* have been most frequently cited by most of the other journals. It was also noted that the *Journal of Forensic Radiology and Imaging*, one of the young journals with its first issue published in 2013, ranked third and sixth in the number of publications and citations, respectively (Table 5). Based on the frequency and pattern of citations among the top ten journals, four clusters could be found: [i] Am J Forensic Med Pathol, Forensic Sci Int, Indian J Med Forensic Med Toxicol, J Forensic Legal Med, J Forensic Sci, [ii] Forensic Sci Med Pathol, J Forensic Radiol Imaging, [iii] Int J Legal Med, Rechtsmedizin, and [iv] Legal Med.

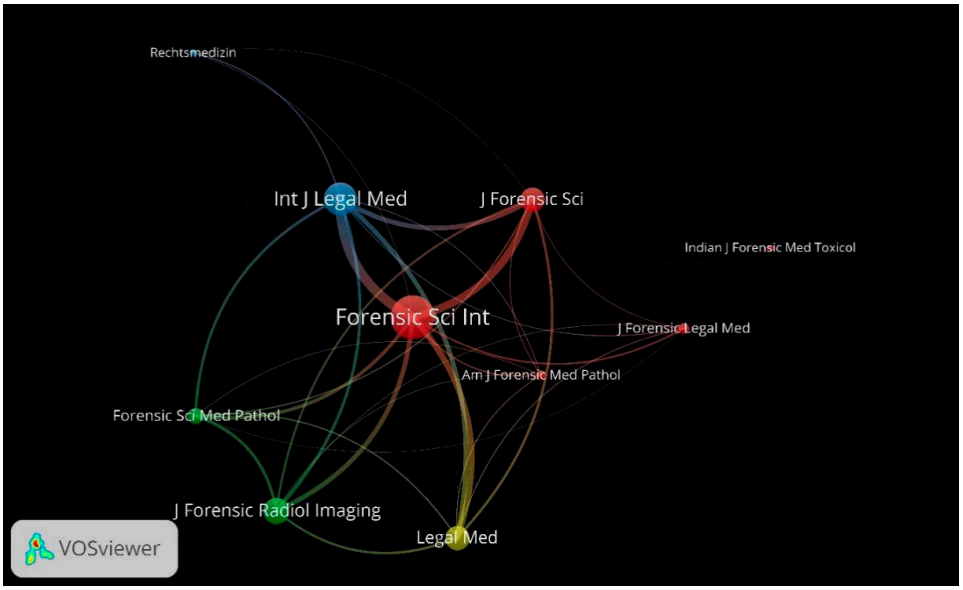


Figure 4. Network visualization map of citation analysis among top ten journals. The size of circles and fonts denotes the total number of documents published in the journals; the thickness of lines indicates the relative frequency of citations between two journals; and the color indicates the clusters of journals.

3.5. Keywords

Out of 3998 keywords, there were 27 keywords that have appeared 30 or more times in the CT-related forensic studies (Table 6). Based on the strength and pattern of co-occurrence/link of the keywords, four clusters could be found (Table 6). The keywords in the same cluster tended to occur together in the articles. The result of the co-occurrence test is displayed on the map in Figure 5, where the size of circles and the thickness of lines denote the relative number of publications and the relative frequency of co-occurrence between two keywords, respectively. When the time of publication is taken into account, it was noted that the keywords colored in yellow such as "Forensic Anthropology", "Postmortem CT", "Cone Beam CT", and "Micro CT" have appeared relatively recently.

Table 6. Keywords that have appeared in 30 or more CT-related articles in the Forensic section of Scopus between 1978 and 2020. The keywords in the same cluster tended to have appeared together.

Keyword	Number of Occurrence	Total Link Strength	Cluster
Computed Tomography/CT	420	544	2
Postmortem Computed Tomography/Postmortem CT/PMCT	293	338	3
Forensic Anthropology	245	318	1
Forensic Radiology	220	358	3
Forensic Science	215	379	1

Table 6. *Cont.*

Keyword	Number of Occurrence	Total Link Strength	Cluster
Virtopsy/Virtual Autopsy	195	338	3
Autopsy	162	220	2
Forensic Pathology	123	167	2
Cone Beam CT	82	103	1
Age Estimation	81	121	1
Sex Estimation/Sex Determination	79	126	1
Forensic Imaging	66	98	3
Forensic Medicine	62	59	2
Forensic	59	66	2
Magnetic Resonance Imaging	54	93	3
Postmortem Imaging	53	106	3
Identification	50	79	1
Forensic Anthropology Population Data	49	59	1
Sexual Dimorphism	44	72	1
Radiology	42	74	2
Forensic Dentistry	37	50	1
Postmortem	36	69	2
Micro CT	36	28	4
Multidetector CT	34	42	1
CT Scan	34	24	2
Forensic Odontology	32	55	1
Forensic Autopsy	30	26	3

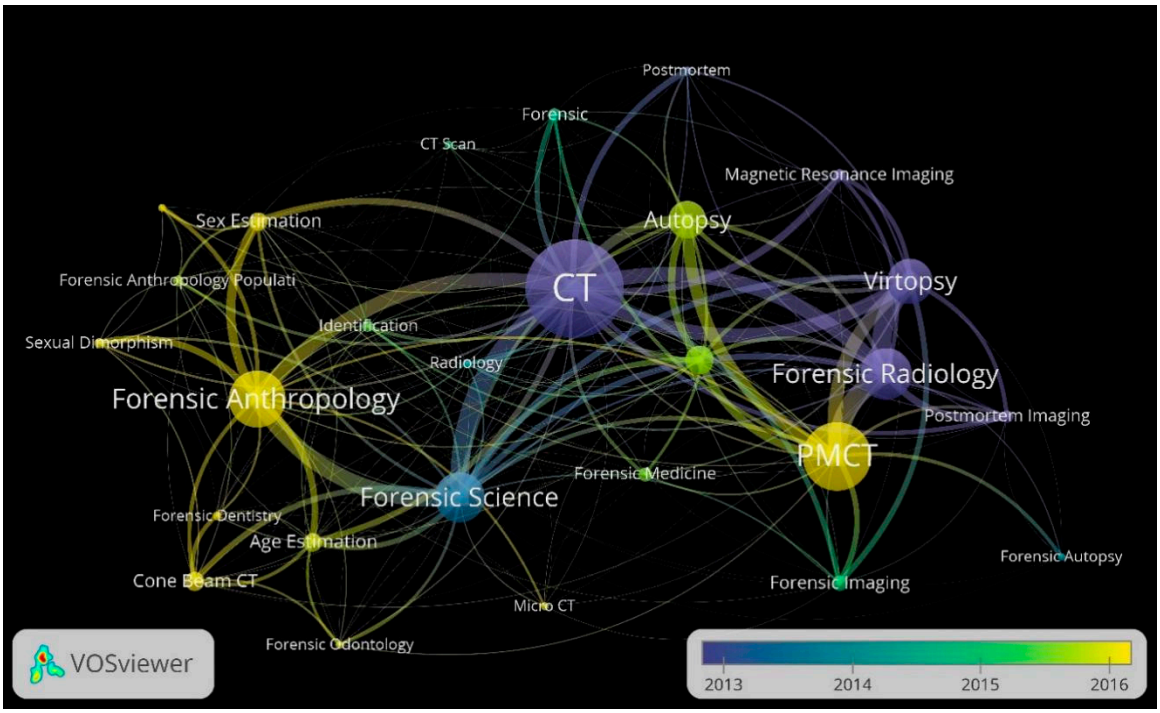


Figure 5. Overlay visualization map of co-occurrence analysis among top 27 keywords. The size of circles and fonts denotes the relative number of documents; the thickness of lines indicates the relative frequency of co-occurrence between two keywords; and the color indicates the clusters of journals. The number of frequencies of the keywords has increased from purple to yellow (purple–blue–green–yellow).

4. Discussion

Bibliometric analysis allows for a quantitative, systematic, and objective assessment on the publications in a field, which helps researchers to have an understanding about the past and current state of the field as well as a holistic insight on its future direction [6,7,10]. Among the earliest topics for the bibliometric analyses was forensic science where the publications of diverse subdisciplines of forensic science in Europe were examined [13,14]. The establishment of digital journal archives (e.g., Scopus, Web of Science, and PubMed) and development of computer software that can analyze the archived data (e.g., VOSviewer) makes the process of bibliometric analysis straightforward and time-efficient. Thus, recent years have seen increasing bibliometric analyses in various fields, e.g., [6,7,15,16].

One of the notable findings in the current study is the rapid increase in the number of articles, particularly since the early 2000s (Table 1). In 2003, Thali and colleagues [4] emphasized and encouraged the utility of imaging techniques such as CT and MRI in the field of forensic science. Interestingly, this year was the first year during which more than ten CT-related forensic articles were published ($n = 11$), and the increasing trend has continued except for 2005, 2014, and 2018. The AGR has fluctuated between 2000 and 2019; however, except for 2001, 2005, and 2018, there were no years with negative AGRs. In other words, the number of publications for most of the past 20 years exceeded (or was the same as) that of the preceding year (Table 1). In 2017, the number of annual publications exceeded 200 for the first time ($n = 202$) and the increasing trend is likely to continue in 2020 as well ($n = 211$ as of 4 November 2020).

Switzerland and United States ranked first and second in both the number of publications ($n = 335$ and $n = 259$, respectively) and citations ($n = 6662$ and $n = 4775$, respectively) (Table 2). Japan ranked third in the number of publications ($n = 224$), but Germany ranked third in terms of the number of citations ($n = 3534$). Cluster analysis in Figure 3 shows which countries have close collaborative relationships. Demir et al. [6] state that geographic location is an important factor in terms of collaborations between countries. However, the result of the current study did not show a clear relationship between the geographic locations and collaborative network of the countries. For example, eight European countries in Figure 3 were divided into four different clusters, and China and France were in the same cluster. It is beyond the scope of the current study to investigate the underlying factors affecting the international collaborations, but it would be a significant topic for future research.

The leading role of Switzerland in the CT-related forensic studies was also evident in the list of most productive institutions (Table 4). Six out of 16 institutions in Table 4, including the top three institutions, are located in Switzerland. Moreover, approximately 23.8% of the articles (496 out of 2084) have been produced by these six Swiss institutions. The rest of the institutions are located in Australia, China, France, Germany, Japan, and the United Kingdom. Interestingly, any institutions from the United States or Italy, which ranked second and sixth in the number of publications, were not listed in Table 4. This is possibly because the large number of publications in the United States ($n = 259$) and Italy ($n = 173$) have been produced by diverse research groups rather than by a small number of leading groups.

Approximately 43.6% of the CT-related forensic studies (909 out of 2084 articles) have been published in five journals (Forensic Science International, International Journal of Legal Medicine, Journal of Forensic Radiology and Imaging, Journal of Forensic Sciences, and Legal Medicine) with the total number of citations of 13,836 (Table 5). Forensic Science International ranked first in both the number of publications ($n = 261$) and number of citations ($n = 5241$). Indeed, the co-citation analysis map in Figure 4 displays the Forensic Science International in the center, which indicates that the articles in the journal have been cited by most of the other journals. Similar results were obtained from previous bibliometric studies in the fields of legal medicine [6] and forensic anthropology [16], where Forensic Science International was listed as the most influential journal.

The keyword analysis revealed four clusters, of which centers (i.e., the keywords with the greatest total link strength of each cluster) were “Forensic Anthropology”, “Postmortem Computed

Tomography", "Autopsy", and "Computed Tomography". This result indicates that CT has been primarily used in two forensic subfields: forensic pathology/medicine and forensic anthropology. Since the development of X-ray CT in 1974, the CT technique has been constantly applied to forensic pathological studies and case reports [9]. The continuous effort to develop advanced techniques at higher resolution has led to a more common application of virtual autopsy (virtopsy) in medical examiners' offices nowadays [17,18]. This trend not only resulted in a plentiful production of articles to validate the utility of CT compared to traditional autopsy or other types of imaging techniques, e.g., [19–21], but also expanded the applicability of CT (e.g., estimation of pupae's developmental age [22]; reconstruction of bloodstain in fabric [23]; determination of non-human skeletal remains [24]). Recently, the need to establish new and efficient processing protocols has increased in the field where CT is applied, e.g., [25]. In the field of forensic anthropology, the CT technique has been introduced relatively recently as shown in the keyword analysis (Figure 5); however, the number of forensic anthropological studies using CT has increased rapidly. Particularly, there has been increasing efforts to develop new models for sex and age estimation using CT, e.g., [26–28], to validate the accuracy of osteometric measurements in the CT scans, e.g., [29,30], and to automate the analysis processes where CT is involved, e.g., [31,32]. In addition, Cone Beam CT has been frequently used to measure the thickness of facial soft tissues and contributed to the field of facial reconstruction and personal identification, e.g., [31,33].

As to the application of VOSviewer for a bibliometric analysis, Demir et al. [6] pointed out two limitations which the current study could also not avoid: a risk of self-citation and a risk of excluding publications written in a non-English language from the analyses. In addition, since the scope of publications analyzed by VOSviewer is determined primarily by the keywords entered during the Document Search process, there is a possibility that a bibliometric study may not include all publications of a targeted field. To avoid this issue, a careful selection of keywords will be required. In this regard, this study used four keywords ("forensic", "legal medicine", "medicolegal", and "computed tomography") to include as many related publications as possible. Lastly, some information presented by VOSviewer may slightly differ from what they actually are because VOSviewer analyzes data as the authors of the original publications literally provided. For example, if an author working in a university hospital used the names of the university and the hospital in two different papers as his/her affiliation, there is no way for VOS viewer to notice it. A careful inspection and verification of the information as well as an effort to avoid these limitations will be necessary in the future research.

5. Conclusions

The use of CT in the forensic context has increased drastically since the early 2000s, which caused the plentiful production of articles. This increasing trend appears to continue as more researchers and institutions include the CT technique in their works and research. At the same time, the scope of CT-related research will likely expand to more diverse subfields of forensic science, which will result in a fruitful production of publications with a variety of topics. In this regard, the current study will be particularly helpful to the researchers who have recently initiated CT-related research by providing them with a holistic insight into the research trend as well as a source of potential collaborations (i.e., productive countries, institutions and authors).

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