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Methodological Review

Mapping the intellectual structure of research on surgery with mixed reality: Bibliometric network analysis (2000–2019)

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ABSTRACT

Objective: The purpose of this study is to view research trends on surgery with mixed reality, and present the intellectual structure using bibliometric network analysis for the period 2000–2019.
Methods: Analyses are implemented in the following four steps: (1) literature dataset acquisition from article database (Web of Science, Scopus, PubMed, and IEEE digital library), (2) dataset pre-processing and refinement, (3) network construction and visualization, and (4) analysis and interpretation. Descriptive analysis, bibliometric network analysis, and in-depth qualitative analysis were conducted.
Results: The 14,591 keywords of 5897 abstracts data were ultimately used to ascertain the intellectual structure of research on surgery with mixed reality. The dynamics of the evolution of keywords in the structure throughout the four periods is summarized with four aspects: (a) maintaining a predominant utilization tool for training, (b) widening clinical application area, (c) reallocating the continuum of mixed reality, and (d) steering advanced imaging and simulation technology.
Conclusions: The results of this study can provide valuable insights into technology adoption and research trends of mixed reality in surgery. These findings can help clinicians to overview prospective medical research on surgery using mixed reality. Hospitals can also understand the periodical maturity of technology of mixed reality in surgery, and, therefore, these findings can suggest an academic landscape to make a decision in adopting new technologies in surgery.

1. Introduction

Along with the increasing development of advanced technology in medical fields, innovative changes have occurred in surgery. One of these changes is the adoption of mixed reality in the surgical context [1]. The birth of virtual reality technology enabled a significant transformation from open surgery to minimally invasive surgery, and this minimally invasive surgery leads to the innovative medical transformation of the surgical environment. The major characteristics of the current surgical environment with mixed reality are as follows: (a) technology-driven innovation, (b) rapidly updated and changing sector, and (c) convergence among different disciplines (*e.g.*, data science, artificial intelligence, cognitive engineering, and other disciplines dealing with cutting edge technologies). Several studies attempted to understand the development and changes of this surgical simulation technology. However, prior studies were implemented in only certain surgical contexts of specific clinical departments [2–4], or implemented in systematic reviews on several selected papers[2,5–7]. This study paid attention that, at this point, research concerning surgery based on mixed reality needs a comprehensive and systematic literature review regardless of a particular clinical domain.

Hence, this study conducted a bibliometric network analysis of surgery using mixed reality to gain a comprehensive understanding of this area and suggest intellectual trends in this field. Bibliometric network analysis is a set of review methodology to analyze all related publications on a specific topic. This review methodology can provide a more relational, contextual, and holistic intellectual landscape concerning specific topics[8].

The specific research questions of this study are the follows:

RQ 1. What is the general intellectual basis of the current research of surgery using mixed reality?
RQ 2. What are the most popular keywords of surgery using mixed reality? And which fields are their studies mostly focused on? What

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is the relationship between popular keywords?
RQ 3. How have they evolved over time, and what is the intellectual trend in the research of surgery using mixed reality?

In summary, by conducting a bibliometric network analysis on published articles to this point concerning surgery using mixed reality, this study aims to offer a thorough intellectual structure of the current research landscape and discuss the popular research topics and their evolution over time. The results of this study could not only provide the generic intellectual structure of surgery with mixed reality but also overview the periodic changes on how surgery with mixed reality has evolved until now. Furthermore, through this study, we could highlight the phenomenological flow that how medical fields adopt advanced technologies and merged.

2. Literature background

2.1. Mixed reality in surgery context

There are several terminologies concerning imaging simulation techniques, and their definition differs by the platform, devices, and interaction [7]. Virtual reality (VR) is a computer-simulated reality that can provide an immersive experience by creating an imaginary world. Augmented reality (AR) involves the real world with the addition of digital elements. Mixed reality (MR) is a mix of aspects from VR and AR, so it allows a person to experience a better sense of realism as the digital scenarios take place in real-world surroundings [9,10].

As the imaging simulation techniques have developed, clinicians have utilized this technology to enhance their operating environment. Some researchers have doubted that this simulation technique would be helpful [11]. However, this emerging technology has brought innovative changes from general surgery to minimally invasive surgery.

Prior medical researchers have identified the detailed utilization of certain imaging simulation technology based on the development of new simulation devices or techniques [2,4,6]. These studies would be valuable to comprehend the most advanced imaging technology in the surgical environment. Meanwhile, most of these findings focus on particular imaging simulation technology or specific surgery so that researchers could obtain separate and limited knowledge on the imaging simulation technology.

2.2. Bibliometric network analysis

Bibliometric analysis is a scientific computer-assisted review methodology that can identify core research or authors, as well as their relationship, by covering all the publications related to a given topic or field [12]. For a literature review, systematic literature review or meta-analysis has been the major research methodology in the medical area, which deals with several restricted publications with sampling procedures and implements content analysis. These methods would be efficient to analyze specialized clinical area or disease. However, this bibliometric analysis can provide abundant and relational information on the topic, thereby the understanding of the overall intellectual landscape can be possible [13,14].

Initial bibliometric analysis mostly based on the author or citation information and examined their intellectual flow and most influential publications [12,15,16]. Lately, bibliometric analysis adopted network analysis and sociometric analysis based on the titles, keywords, and abstract data [17–20].

3. Data collection and methodology

3.1. Dataset collection

To collect raw data, we used the journal database exported from Web of Science, Scopus, PubMed, and IEEE digital library. Web of Science and Scopus are the most authoritative databases of peer-reviewed papers. Moreover, we additionally chose PubMed and IEEE digital library to refer to domain-specialized knowledge: medical and engineering fields. Based on the research framework, we composed our query as follows:

Query = (“surgeon” OR “surgical”) AND (“augmented reality” OR “virtual reality” OR “virtual immersive reality” OR “mixed reality” OR “immersive reality”)

The data retrieval was implemented in 1 Jul 2019, and 6263 articles were initially searched. These are articles from 2000 and written in English. Based on the set, we extracted data that were duplicated and have no abstract. Thus 5897 articles were obtained. The bibliometric data of title, author name, publication year, journal, author keywords, and abstract were retrieved.

3.2. Dataset pre-processing and refinement

Among 5897 abstracts, we classified noun data and composed text corpus. Then, data refinement and normalization was conducted with the following steps: [1] eliminate ordinary terminologies that are generally used in abstract (*e.g.,* literature discussion aim results implementation purpose impact method), [2] compose synonym text sets which indicate same meanings (e.g., VR and virtual reality, robot, and robotics), [3] unify singular and plural of same words to the singular words, and [4] reflect academic compound noun based on the author keywords data. The refinement results were accepted, so 14,591 words of 5897 abstracts were selected for the following steps. Data pre-processing and refinement was conducted by Python 3.7 [21].

3.3. Analysis strategies

After the selection of text corpus, datasets were arranged as a document term matrix by occurrence and then transformed into a co-occurrence matrix using the Ochiai-Salton algorithm, which is symmetric. To filter generally used terminology, this review adapted TF-IDF (term frequency/inverse document frequency) text-mining method, and a semantic bibliometric network was derived [22]. The software used to extract the networks and visualization was *NetMiner* 4.0, since this program specializes in constructing semantic network analysis and provides a graphical illustration of the network [23].

Data analysis was conducted by four steps to highlight the intellectual structure of surgery with mixed reality. Fig. 1 reveals the overall representation of this research methodology.

- *Descriptive Analysis*: based on the publication and journal frequency, the primary research domain concerning surgery with mixed reality could be driven.
- *Bibliometric network Analysis*: through frequency and degree centrality of keywords (2000–2019), influential concepts in surgery with mixed reality could be analyzed. After that, to figure out the intellectual trend of the research in surgery with mixed reality, time series analysis was implemented by division into four stages (2000–2004, 2005–2009, 2010–2014, and 2015–2019). *PFnet* algorithm was adapted to extract and visualize core network with high co-occurrence value.
- *Qualitative In-depth Analysis (Content analysis):* this paper classifies the most cited literature review papers concerning surgery with mixed reality and conduct in-depth qualitative analysis so as to deduct the contextual interpretation of keywords. The results of this qualitative analysis were utilized as supporting evidence for network analysis.

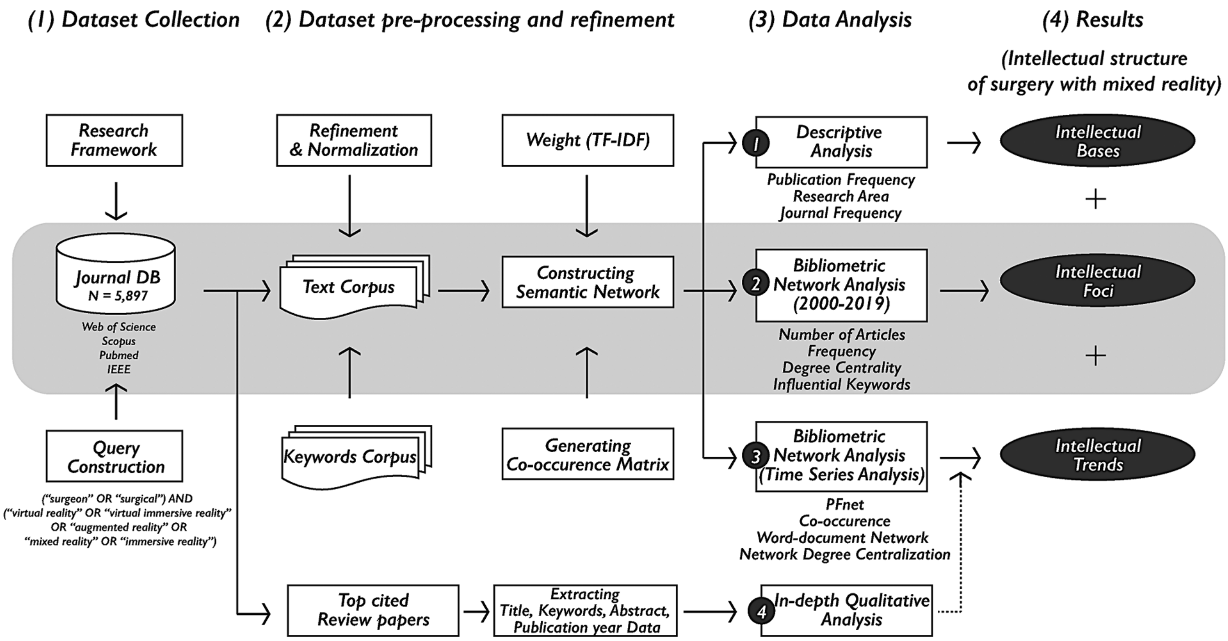

Fig. 1. Research Methodology.

4. Metadata analysis and findings

4.1. Descriptive analysis

Through periodical distribution of researches and journal frequency data on surgery adapting mixed reality, we could interpret the research popularity and predominant research domain. As shown in Fig. 2, published articles on the topic from 2000 are gradually increased, thus represent the high level of academic interests and popularity ($R^2 = 0.950$).

The statistical results of journal frequency were deducted from 657 journal lists of 5897 abstracts. Fig. 3 reveals the most influential journal lists from 2000 on the researches concerning surgery with mixed reality. *Surgical endoscopy and other interventional techniques* show the highest number of articles at 192 publications, followed by *Surgical Endoscopy, Journal of Surgical Education, Studies in Health Technology and Informatics, International Journal of Computer Assisted Radiology and Surgery*, and *Neurosurgery*, all which hold more than 100 papers on this topic. *Journal of Biomedical Informatics* retains ten papers from now on.

According to the journal classification on Web of Science, *Surgery* (54.8%) is the most predominant academic area which deals with researches on the surgery with mixed reality. The following research

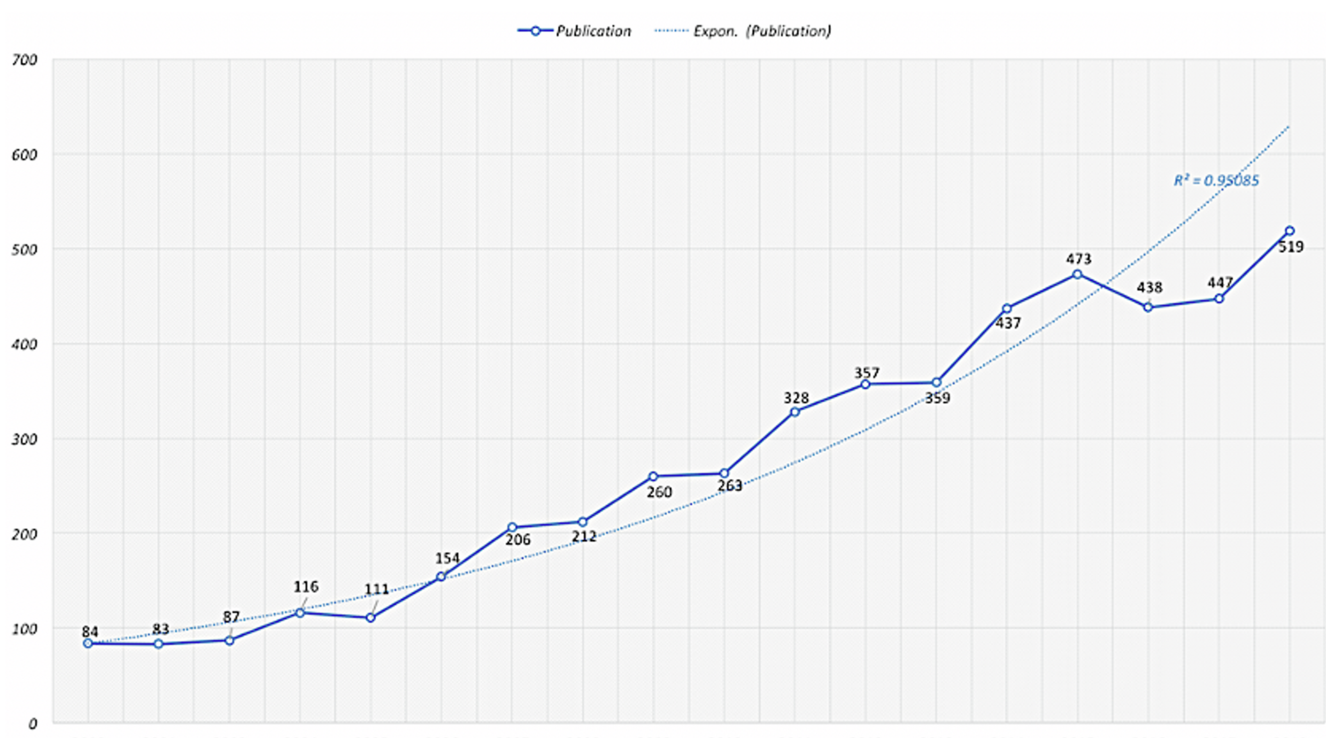

Fig. 2. Publication Frequency (2000–2019).

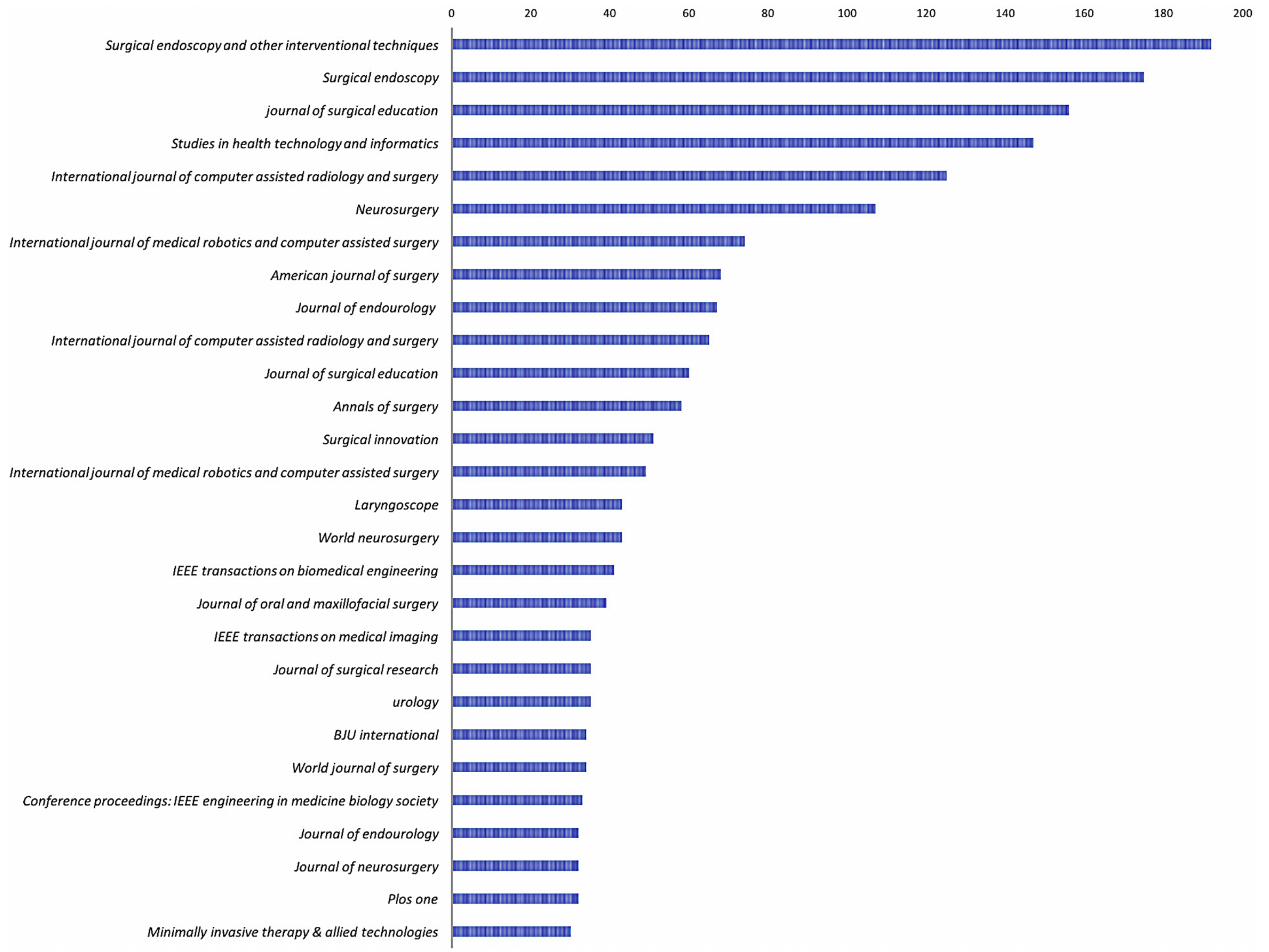

Fig. 3. Top influential journal lists (2000–2019).

domains were *Engineering* (13.1%), *Computer science* (9.0%), *Neurosciences neurology* (8.1%), *Radiology nuclear medicine medical imaging* (8.1%), *Urology nephrology* (7.3%), *Education educational research* (5.6%), *Orthopedics* (4.7%), *Otorhinolaryngology* (3.7%), and *Health care sciences services* (3.0%). As mentioned earlier, research concerning surgery with mixed reality is implemented in the domain of surgery part as an application area and engineering part which deals with targeted advanced technology. Especially *Neurosciences neurology, Urology nephrology, Orthopedics,* and *Otorhinolaryngology* represent the primary applicable medical domain on the topic.

4.2. Bibliometric network analysis: 2000–2019

Based on the frequency and degree centrality of 14,591 keywords, influential concepts in surgery with mixed reality are drawn. Table 1 reveals 40 predominant keywords according to the numbers of articles and frequency. Fig. 4 visually represents a word cloud of 500 words in the studies based on frequency data, with larger texts indicating a higher frequency.

The results show that the keywords set of studies on surgery with mixed reality is quite similar between the numbers of articles and frequency. According to the frequency, “training” reveals the most influential keywords and “virtual reality”, “surgeon”, “task”, “performance”, “simulator”, “time”, “augmented reality”, “skill”, “simulation”, “imaging”, and “data” are followed. This finding shows that mixed reality technology is mainly utilized for surgeons to train for surgery practice and the conceptualizations of virtual reality and augmented reality are more predominant than mixed reality from 2000 to 2019.

4.3. Bibliometric network analysis: time series analysis

To understand the intellectual trend and evolution of the research in surgery with mixed reality, network analysis is implemented by dividing into four periods (2000–2004, 2005–2009, 2010–2014, and 2015–2019). This five year period classification is decided due to significant increases of the publications in Fig. 2 (2005–2007, 2010–2011, and 2013–2015). Core networks with high co-occurrence value are visualized with *PFnet*. Tables 2 and 3 represent respectively the brief information of periodical articles classification and the properties of time series networks.

As shown in Fig. 2, the number of papers has gradually increased from period 01 to 04. The number of keywords has also steadily grown, and this growth rate is higher than the increasing rate of the number of documents. The values of word-documents networks also present more abundant networks in the process of time. These findings could provide empirical evidence that researches on surgery with mixed reality have been growing in terms of quantitative standards as well as qualitative standards.

In order to highlight the shape of the intellectual map as well as knowledge evolution on the topic, we compared the detailed properties of bibliometric networks by period. Based on the word-documents network, we extracted the core networks by co-occurrence and

Table 1
Top 40 keywords according to the number of articles and frequency (2000–2019).

Rank	Keyword	No. of article	Rank	Keyword	Frequency
01	virtual reality	2641	01	training	5892
02	surgeon	2544	02	virtual reality	5768
03	training	2345	03	surgeon	5268
04	time	1907	04	task	4151
05	performance	1844	05	performance	4025
06	simulator	1642	06	simulator	3793
07	task	1611	07	time	3761
08	data	1463	08	augmented reality	2590
09	skill	1423	09	skill	2499
10	simulation	1404	10	simulation	2448
11	imaging	1121	11	imaging	2394
12	laparoscopic surgery	1108	12	data	2335
13	experience	1105	13	trainee	2052
14	technique	1099	14	laparoscopic surgery	2051
15	trainee	1067	15	novice	1880
16	technology	1045	16	experience	1699
17	virtual reality simulator	993	17	error	1654
18	augmented reality	990	18	technique	1630
19	assessment	952	19	technology	1591
20	error	882	20	assessment	1502
21	novice	866	21	virtual reality simulator	1424
22	environment	833	22	expert	1233
23	improvement	791	23	environment	1151
24	operating	740	24	improvement	1151
25	information	665	25	operating	1143
26	3d	664	26	3d	1076
27	expert	660	27	information	940
28	real time	637	28	real time	923
29	surgical training	624	29	tissue	912
30	operating room	574	30	navigation	891
31	practice	571	31	module	871
32	surgical procedure	536	32	video	850
33	tissue	527	33	practice	839
34	video	509	34	movement	816
35	visualization	492	35	operating room	803
36	movement	491	36	surgical training	781
37	anatomy	491	37	force	756
38	navigation	471	38	anatomy	732
39	minimally invasive surgery	469	39	trainer	720
40	software	467	40	visualization	712

visualized as *PFnet* algorithm [24,25]. The number of core networks is calculated weighted value according to the number of documents.

Network degree centralization is a measurement to evaluate the degree of inequality as a percentage of that in a perfect "star network": the most unequal type of network. The value of network degree centralization has slightly increased in the time period. Therefore, more distinct differences between influential keywords have become larger, as shown in the minimum and maximum value of degree centrality of Table 3 [26,27]. This result indicates that major nodes have been more influential in period 04 than period 03. Since the network of *PFnet* is efficiently visualized between 100 and 200 nodes, the network of period 03 has fully abundant links, and this tendency is connected to period 04.

Visualization of core keyword occurrence networks, by *PFnet* of each period, is shown in Figs. 5 and 6. Keywords with high occurrence are represented as bigger and darker nodes. The figuration of network has become more complex, so it is hard to compare each keyword by period. The top 50 keywords based on the degree centrality between period 01 and 04 are arranged in Table 4. If we compare two periods' degree centrality and analyze the configuration of networks with connected keywords, intellectual evolution in the researches concerning surgery with mixed reality could be analyzed. As mentioned earlier, this paper classifies the most cited literature review papers concerning surgery with mixed reality and conduct in-depth qualitative analysis. All researchers of this paper participated in the in-depth analysis. The results of the analysis are utilized as supporting evidence for this section.

By comparing the network and keywords lists, we found that the top 50 core keyword sets on the topic differ little from period 01 to 04. This result shows that intellectual networks of surgery with mixed reality have been growing with stable nodes of sub networks to constitute a well-focused intellectual structure. The dynamics of the evolution of keywords in the structure throughout the four periods and summarized with four aspects: (a) maintaining predominant utilization tool for training, (b) widening clinical application area, (c) reallocating the continuum of mixed reality, and (d) steering advanced imaging and simulation technology.

A. Maintaining predominant utilization tool for training

Throughout the whole period, "training" has kept in the top core keywords in the bibliometric network in the studies on surgery using mixed reality [28]). Other keywords as "task", "performance", "skill", "trainer", "trainee", "technique", "novice", "expert", and "education" which closely related to surgical training, are extracted in core bibliometric networks. The keyword "training" is directly connected with "virtual reality", "simulator", and "practice" in period 1. From period 2 to 4, this closely related connection between "virtual reality" and "training" is maintained by generating other sub-network: "performance" in period 2, "surgeon" and "skill" in period 3. In period 4, secondary sub-networks are generated based on "performance" and "skill" sub-networks. Research on this topic generally addressed the efficiency on how virtual reality simulation could help novice surgeons to enhance their comprehension and training for a successful surgery. Based on these findings, recently, researchers have detailed more solutions and other factors to improve surgical skill with mixed reality: (1) the development of scenario-based surgical contents [29,30]; (2) more refined and sophisticated detecting tools for evaluating operational performance [7,31,32]; (3) multi-evaluation criteria of the surgical outcomes [33], and (4) configuration of the virtual reality environment as a real surgical setting [34].

B. Widening clinical application area

As the minimally invasive surgery evolves with the development of robotic surgery, it could be possible to induce higher-level endoscope manipulation skills with single port operation, better surgical outcome, and better patient recovery. In the core network, several keywords such as "minimally invasive surgery", "laparoscopic surgery", and "laparoscopic cholecystectomy" were derived. Early imaging simulation technology, primarily utilized as a training tool for novice surgeons as mentioned above, and this technology was adapted to diversified clinical areas. Recent and detailed clinical applications on surgery with mixed reality were analyzed through in-depth literature reviews.

Recently, surgery using mixed reality is generally adapted to the following clinical domains: otolaryngology, neurosurgery, ophthalmology, urology·gynecology, dentistry.

Otolaryngology utilizes this technology on endoscopic sinus and skull base surgery in that patient's anatomy can be reproduced, and interaction with endoscopic handling and realistic haptic feedback is possible [35]. Neurosurgery mainly uses augmented reality regarding neurovascular applications and neuro-oncological pathologies [5,7]. Ophthalmology utilizes virtual reality technology to implement surgical training or surgical imaging analysis in ophthalmic surgery and vitreoretinal surgery [6,11]. Urology and gynecology are the clinical areas actively utilizing minimally invasive surgery because they have to perform surgery with nerve tissues and prevent perioperative

Fig. 4. Word cloud of 500 words concerning surgery and mixed reality (based on frequency, 2000–2019).

morbidity. They are considering the development of non-technical skills assessment tools for better operational performance and utilization of augmented reality in a real surgical setting [36,37]. Dentistry adopts virtual reality and augmented reality to use for educational motor skill training, clinical testing of maxillofacial surgical protocols, investigation of human anatomy, and the treatment of patients with dental phobia [2,38].

To sum up, the use of this imaging simulation technology allows a surgeon to maintain their view on the operative site permanently. It is useful for locating structures, guiding resections, and planning the craniotomy with more precision, decreasing the risk of injury.

C. Reallocating the continuum of mixed reality

The most significant change observed is the emergence of "augmented reality" as retain top core keyword until 2019. Augmented reality technology is evaluated as the most suitable advanced medical technology to the real surgical environment, providing virtual manipulated images based on real patient's anatomic structure [2,5,39]. Making 3D imaging reconstruction and configuration based on CT or MRI, the preview of surgical procedure by visualization of blood vessel or nerve tissues, are the main recent topics on surgery with mixed reality [31].

Early studies on virtual reality with surgery attempted to figure out the efficiency of this technology for surgical training. There is much literature that argues for the need of economic investment to establish a virtual surgical training setting [11]. Consequently, surgical training with virtual reality is generally considered as more adequate tool for novice surgeons to improve their surgical ability, compared with expert surgeons.

To sum up, "augment reality" reveals more predominant keywords than "virtual reality" in network configuration, but utilization domains using two types of technology could be different. It is hard to conclude

Table 3
Properties of time series networks.

	Period 01 (2000–2004)	Period 02 (2005–2009)	Period 03 (2010–2014)	Period 04 (2015–2019)
Network degree centralization				
index	9.26%	9.53%	9.65%	12.70%
Distribution of degree centrality*				
Mean of degree centrality	0.020	0.013	0.010	0.010
STD.DEV.	0.016	0.016	0.012	0.013
Min. of degree centrality	0.010	0.007	0.005	0.005
Max of degree centrality	0.111	0.107	0.106	0.136
Extracted PFnet information				
links in the original network	101	8524	15,987	16,942
links in the *PFnet* (R = ∞, Q = N-1)	101 (100%)	149 (1.75%)	199 (1.25%)	199 (1.18%)
total weight in the original network	35.30	784.59	1206.64	1203.14
total weight in the *PFnet* (R = ∞, Q = N-1)	35.30 (100%)	42.84 (5.46%)	52.15 (4.32%)	50.52 (4.19%)

Table 2
Brief information of time series analysis.

	Total Period (2000–2019)	Period 01 (2000–2004)	Period 02 (2005–2009)	Period 03 (2010–2014)	Period 04 (2015–2019)
No. of Keywords	14,576	2845	4985	7428	9165
(%)	(100%)	(19.52%)	(34.20%)	(50.96%)	(62.88%)
No. of Docs	5895	481	1095	1954	2365
(%)	(100%)	(8.16%)	(18.58%)	(33.15%)	(40.12%)
Word-Documents Network	256,624	17,414	43,692	87,602	107,916

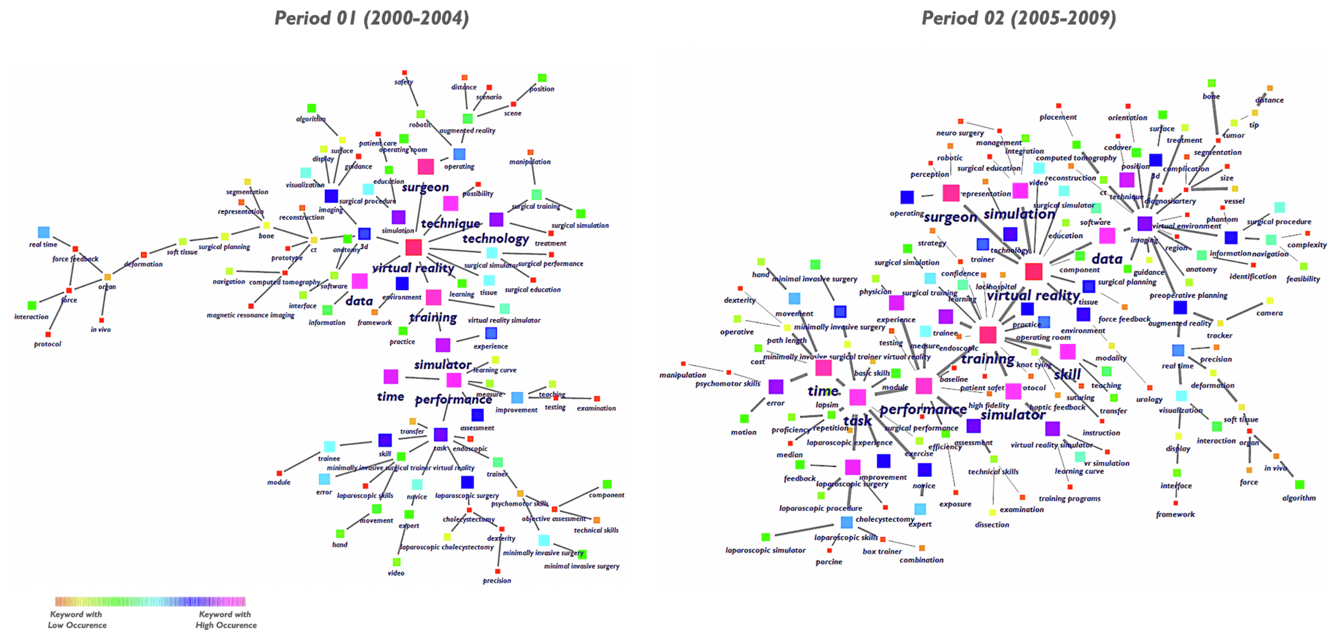

Fig. 5. Visualization of core keywords occurrence networks with PFnet in the Period 01 (left) and Period 02 (right).

that augmented reality would substitute for virtual reality in surgical environment by analyzing the bibliometric network. Therefore, this continuum from virtual reality to augmented reality would be connected to mixed reality technology in the surgical environment.

D. Steering advanced imaging and simulation technology

Since the mixed reality mainly deals with visual technology, keywords regarding imaging technology represent a high degree centrality value. Based on the core keywords of period 1 as “imaging”, “CT”, “3D”, “simulator”, “visualization”, and “virtual reality simulator”, several words as “calibration”, “reconstruction”, “real time”, “tomography” additionally emerged in period 4. Research of period 1 generally attempted to discover the clinical effectiveness of surgical simulation using virtual reality technology or adoption to surgical training contents [40,41]. From period 2, more high level of the terminology related to imaging technology appeared concerning surgical imaging reconstruction, which mainly combines CT or MRI images to 3D visualization. Studies in period 3 show diverse clinical trials using this technology: otolaryngology, neurosurgery, urology, gynecology, orthopedics, and robotic surgery [39]. Recent researches on surgery with mixed reality proposed more interdisciplinary converged research based on 3D printing, haptic, navigation technology with mixed reality [5,28,42,43]. As the technical development get highly advanced, recent researches on the topic deal with more sophisticated and specialized on specific surgical setting.

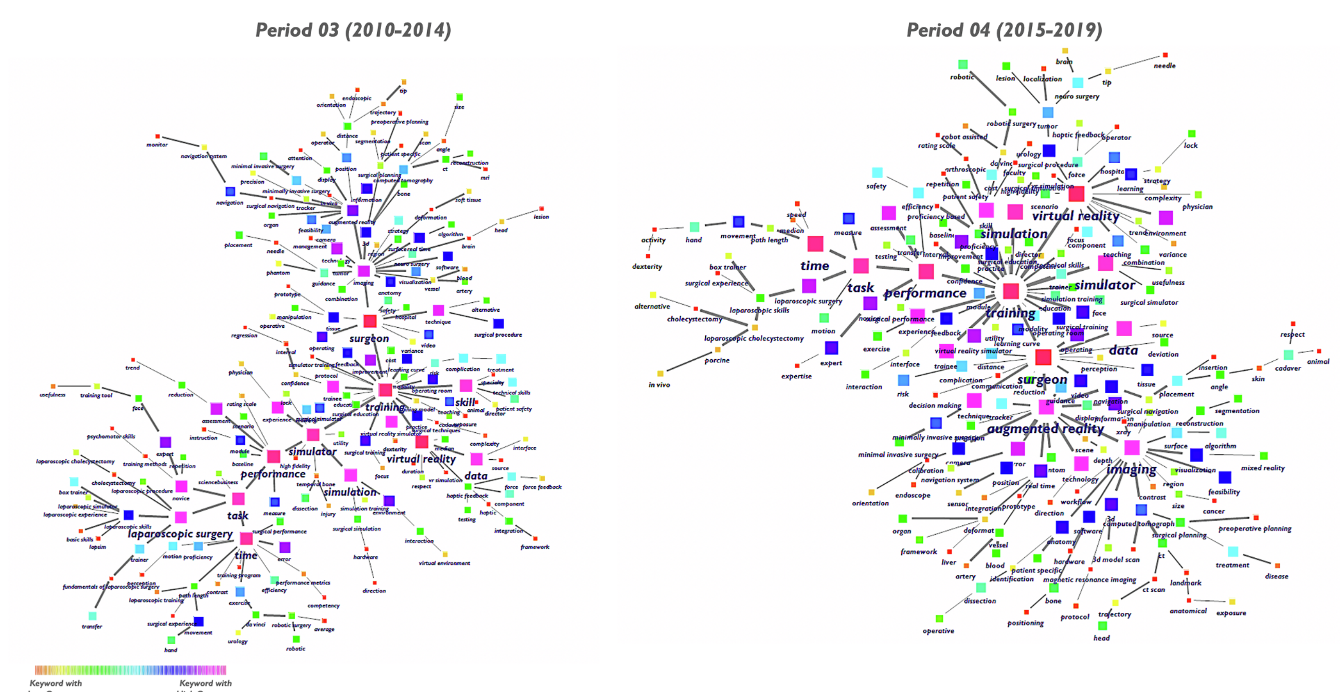

Fig. 6. Visualization of core keywords occurrence networks with PFnet in the Period 03 (left) and Period 04 (right).

Table 4
Comparison of time series clustering results for the 2000–2004 and 2015–2019 periods.

Period 01 (2000–2004)	In-degree	Period 04 (2015–2019)	In-degree
virtual reality	0.111	training	0.136
task	0.081	augmented reality	0.075
performance	0.071	virtual reality	0.070
imaging	0.051	imaging	0.070
ct	0.051	surgeon	0.065
3d	0.051	performance	0.040
training	0.040	skill	0.030
organ	0.040	task	0.025
minimally invasive surgical trainer virtual reality	0.040	real time	0.025
force	0.040	tumor	0.020
bone	0.040	time	0.020
augmented reality	0.040	simulator	0.020
technology	0.030	laparoscopic skills	0.020
surgical training	0.030	deformation	0.020
surgical simulator	0.030	computed tomography	0.020
surgeon	0.030	vessel	0.015
software	0.030	surgical planning	0.015
simulator	0.030	surface	0.015
simulation	0.030	software	0.015
psychomotor skills	0.030	simulation	0.015
operating	0.030	proficiency	0.015
force feedback	0.030	placement	0.015
cholecystectomy	0.030	neuro surgery	0.015
trainer	0.020	learning	0.015
trainee	0.020	laparoscopic cholecystectomy	0.015
testing	0.020	force	0.015
technique	0.020	da vinci	0.015
surgical planning	0.020	ct	0.015
surface	0.020	calibration	0.015
soft tissue	0.020	cadaver	0.015
skill	0.020	anatomy	0.015
scene	0.020	3d	0.015
robotic	0.020	visualization	0.010
novice	0.020	treatment	0.010
movement	0.020	trajectory	0.010
minimally invasive surgery	0.020	tip	0.010
laparoscopic surgery	0.020	technology	0.010
expert	0.020	technique	0.010
environment	0.020	technical skills	0.010
education	0.020	surgical procedure	0.010
dexterity	0.020	surgical navigation	0.010
deformation	0.020	strategy	0.010
data	0.020	skin	0.010
anatomy	0.020	size	0.010
visualization	0.010	scene	0.010
virtual reality simulator	0.010	robotic surgery	0.010
video	0.010	reconstruction	0.010
treatment	0.010	position	0.010

5. Discussion and future research agendas

5.1. The future directions of the virtual reality and augmented reality in surgery

Based on the prior findings, we could prospect the challenging topics concerning the surgery with the virtual/augmented reality technology. First of all, the initial adoption of virtual reality as a tool for surgical training would continue, therefore, more sophisticated technology for detecting surgeons' movement or reducing the difference between the virtual setting and the real surgical environment. Moreover, the wide range of clinical applications of this virtual/augmented reality technology in surgery could accelerate the development of remote surgery. With the rapid evolution of 5G, this communication network technology would accelerate the mutual technical growth of this intelligent surgical environment.

Along with these technological trends, this study suggests several attempts for intelligent surgery with virtual/augmented reality technology. Above all, the development of a costumed device for surgical behavior. The use of a general-purpose device like *Hololens* or *Google Glass* which aim to adapt from education domain to the entertainment industry, a more professional and exclusive medical equipment which can reflect virtual/augmented reality with real surgical setting should be considered. The extracted data from this kind of surgical device could also accelerate intelligent medical service with big data and AI technology.

5.2. The role of mixed reality for the intuitive interaction between surgeon and robotics

The healthcare domain is evaluated as one of the dominant public sectors that are going to lead virtual · augmented reality market in twenty years, and among this healthcare domain, future surgery is expected to accomplish dramatic technical development [44,45].

The technological development of imaging simulation has heralded swift innovation of surgical procedure by integrating to robotic surgery. This robotic surgery enables the implement of minimally invasive surgery with this imaging simulation technology and communication infrastructure. Therefore, this means that an intelligent surgical environment with remote surgery would become our reality, not a laboratory experiment.

Virtual reality provides immersion based on artificial settings, and augmented reality conveyed a sense of reality based on the real world. Compared with this, mixed reality is regarded as the maximized technology in terms of data usability and effectiveness by advanced haptic technology as well as visual imaging processing.

Both mixed reality and robotic technology have been promising technologies until recently, but it is hard to find the intersecting point between these two technologies. As IRON lab highlighted, it would be crucial how mixed reality technology plays a role as an intuitive interface in the interaction between surgeon and robotics in the future [46,47].

Despite this technological optimism, many clinicians and researchers point out the limitations or drawbacks of these changes: personal information and security, responsibility of medical accidents, and even economic effectiveness. Therefore, legal, cultural, ethical issues, as well as clinical efficacy of mixed reality technology in surgery, should be discussed, and diversified interpretations and profound considerations on humanity should be preceded.

6. Conclusion

This study aims to review the development, changes, and relationships of mixed reality in surgery by conducting a comprehensive literature review on former medical and engineering studies. To cover comprehensive and relational analysis, we implemented a bibliometric analysis based on the article database about the topic. This big data concept enables the handling large and complex bibliometric data sets using a series of advanced computer-based techniques, so it allows a multi-dimensional review approach.

The results of the study show that academic interest in surgery with mixed reality has gradually increased from 2000, and clinical application areas using this technology also are expanded. Based on the periodical changes, we implemented a time series review with four periods, and detailed periodic analysis was conducted with influential keywords. These findings could provide valuable insights into technological innovation and research trends of mixed reality in surgery until now. In a concrete way, the results of this study could not only provide the generic intellectual structure of surgery with mixed reality but also overview the periodic changes on how surgery with mixed reality has evolved until now.

Results can help clinicians to review the periodic development of mixed reality in surgery with a comprehensive perspective. Prior studies implemented in only certain surgical contexts of specific clinical departments, therefore clinicians hardly figure out the differences in their clinical applications compared with other disciplines in the entire technological development of mixed reality in surgery. Through this study, clinicians could understand the periodical maturity of technology concerning mixed in reality surgery, so the results of the study could estimate the feasibility or applicability of the maturity of the technology. In the managerial perspective, hospital executives could comprehend the state-of-art research paradigm and prospective medical research on surgery using mixed reality. Therefore these findings can suggest a kind of an alternative tool for decision making, which can improve both patients' healthcare outcomes and economic value. Moreover, the results of this study could help researchers who are not familiar with mixed reality in surgery context to grasp the overall academic landscape through the predominant conceptualizations and their relationships on mixed reality in surgery.

This study could help other researchers to comprehend the current body of knowledge and stimulate their academic inspirations for future studies concerning surgery using mixed reality. Future research is recommended to implement co-citation and co-authorship analysis to identify more detailed academic stream according to the technical development of surgery with mixed reality.

CRediT authorship contribution statement

Jieun Han: Conceptualization, Methodology, Writing - original draft, Software. **Hyo-Jin Kang:** Conceptualization, Writing - review & editing, Software. **Minjung Kim:** Software, Resources, Visualization. **Gyu Hyun Kwon:** Supervision, Conceptualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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