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A 25-year bibliometric study of implantable energy harvesters and self-powered implantable medical electronics researches

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ABSTRACT

Organisms and surrounding environment are filled with energy that can be converted into electricity by implantable energy harvesters (IEHs). More and more implantable medical electronics (IMEs) are evolving into self-powered devices with the support of the IEHs to break the limitation of service life of batteries used in them. Numerous researches aim to achieve the final goal of self-powered implantable medical electronics (SIMEs). After around one quarter century of research, it is an appropriate time to review the trend and prospect the future of related studies about IEHs and SIMEs. Based on the publications extracted from Web of Science (WOS) over the past 25 years (1995–2019), IEHs and SIMEs are analyzed and summarized based on bibliometric and visualization methods. Evolution trends and research characteristics of five types of IEHs and several highly representative SIMEs are discussed in depth. The findings show that implantable nanogenerator is the most concerned research topic and its research scale is expected to develop rapidly in the future. In addition, the publications of the promising SIMEs for clinical applications have also been highlighted and reviewed.

1. Introduction

Implantable medical electronics (IMEs) that are implanted into human body to detect, prevent and cure diseases, such as cardiac pacemaker and deep brain stimulator, have developed rapidly in recent decades. At the same time, there are still many challenges in this field. In particularly, most energy supplies of IMEs are relying on lithium batteries, which are limited by their insufficient ability to store enough electricity and difficulty in achieving a small scale. Fortunately, there are abundant energies *in vivo* that can be utilized to power IMEs. Such as mechanical energy produced by the motion of respiration, muscle stretching and contraction, heart beating and solar energy through the skin [1–3]. If these energies could be harvested and converted into electricity by intelligent devices or methods, the problem of the limited lifetime of IMEs might have a solution.

Implantable energy harvesters (IEHs) have been demonstrated over the past decades, which can convert energy into electricity *in vivo*. For instance, nanogenerator based on piezoelectric or triboelectric effects can harvest biomechanical energy of heart beating or the ultrasonic energy *in vitro*. By using flexible materials, nanogenerator can be easily fabricated in various required shapes. Nanogenerator can generate a voltage up to kilovolt from unordered mechanical motion. The significant challenges of it include the current improvement, long-term testing, minimization and biodegradability. Biofuel cell can harvest chemical energy from the

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redox reaction of glucose in living organisms [4–7]. The critical issues and challenges of biofuel cell are output performance improvement and long-term function *in vivo*. An automatic power-generating system (AGS) consists of an automatic wristwatch and an electromagnetic generator, which is a long-lasting device and can harvest the biomechanical energy of human motions to power implantable electronics. The flexibility, volume and weight might be the challenges to AGS in the future. Implantable solar cell is a kind of transcutaneous energy transferring devices, which can convert the optical energy from the external body. It generally cannot be implanted too deeply. The most significant challenge of implantable solar cell is the output performance improvement. The endocochlear potential device is a very small category because its output performance still being improved. However, due to its unique structure, the endocochlear potential device can be utilized in the vicinity of the ear, eye and brain. So it is a significant part for SIMEs. The invention of IEHs will be of great help in solving the challenge of limited battery life of IMEs. In addition, researchers have developed various prototypes of SIMEs such as symbiotic cardiac pacemaker and self-powered biosensors, which have substantially promoted the research fields of IEHs and SIMEs.

To analyze the research status and development trend of IEHs and SIMEs more precisely, bibliometric and visualization methods are introduced in this work. Bibliometric is commonly used to analyze academic publications quantitatively, and visualization of the analysis results is an intuitive presentation to make conclusions be interpreted more conveniently [8]. Five main types of IEHs, including nanogenerator, automatic power-generating system, solar cell, biofuel cell and endocochlear potential device, and various SIMEs based on these IEHs, have been analyzed and discussed systematically. Specifically, implantable nanogenerator is discussed in detail for its excellent performance and rapid development [9].

Data is obtained from the online Web of Science (WOS) database hosted by Clarivate Analytics. The retrieval time is from 1995 to 2019. By analyzing the systematic reviews and description of IEHs and SIMEs in previous publications, we define the search strategy by using 40 keyword groups as the Topic Subject (TS) in different search timespan to retrieve in the WOS Core Collection. It includes ten indexes: SCI-EXPANDED, SSCI, A&HCL, ESCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, CCR-EXPANDED, IC. At the same time, the search results contain “All language” and “All document types”.

2. Analyses of implantable energy harvesters

2596 records of publications on IEHs have been retrieved from WOS. We identify 352 records whose contents are related to devices served as a powering system for IMEs. Among the 352 records, 53 publications have achieved implantations. Fig. 1 shows the growth pattern of the five types of IEHs from 1995 to 2019. Some phenomena can be presented as follows:

Firstly, the records of relevant publications on implantable nanogenerator have increased much faster than that of other four types of IEHs. The growth pattern of implantable nanogenerator is closed to the cubic curve (Fig. 1). Compared with solar cell, automatic power-generating system and biofuel cell, it can be found that nanogenerator first reported as a power source for SIMEs in 2006, is relatively new but most rapidly evolving devices for biomedical applications. The rising tendency of researches on implantable nanogenerator is similar to the whole field of nanogenerator [10]. In the period of 2016 to June 2019, the number of new publications of implantable nanogenerator has exceeded the total number of previous years, which shows that nanogenerator as a power source for SIMEs is widely recognized and concerned.

Secondly, according to the screening result, research on solar cell as implantable power source for IMEs began in 1995 [7]. Even

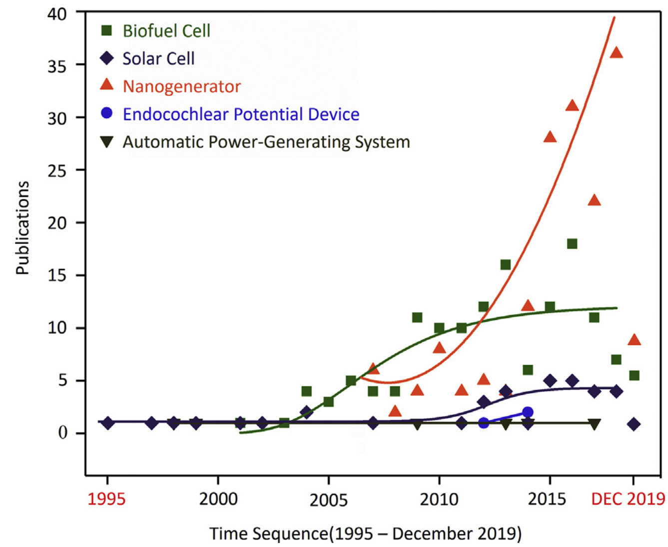

Fig. 1. Nonlinear fitting of the growth trend of five types of IEHs.

though it is the earliest research of IEHs, the research scale about it is not the largest one at present. After implanted into the living body, the scattering and absorption between light and biological tissues will reduce the optical energy efficiency, which is one of the main obstacles to the development of implantable solar cells [11].

Additionally, we estimate the scale of five types of research fields by considering the number of publications, citation frequency and impact factors (IF). As shown in Fig. 2, the total number of publications corresponds to the red axis on the left side. The citation frequency and the impact factors correspond to the blue axis on the right side. The shaded portions indicate the data of IEHs that have been realized in implantations. The total number of publications, citations and impact factors of implantable/implanted nanogenerator are (168/31, 11,134/1812, 1601.545/409.678), respectively. Meanwhile, the statistics data of endocochlear potential device, automatic power-generating system, solar cell and biofuel cell are as follows: (3/2, 151/99, 39.1/33.927), (6/2, 216/50, 34.25/2.039), (40/10, 510/188, 145.486/53.492), (141/9, 8101/726, 744.302/63.955). The scales of these data are from large to small,

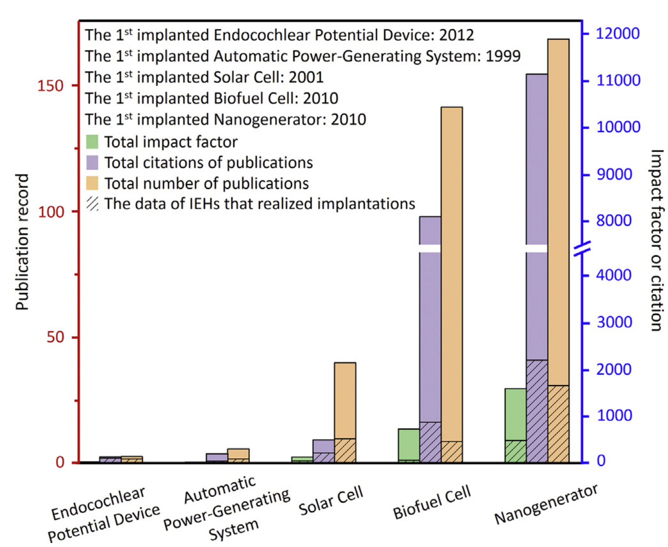

Fig. 2. Statistics of publications records, impact factors and citations of IEHs.

nanogenerator, biofuel, solar cell, automatic power-generating system and endocochlear potential device.

We use VOSviewer to create a citation and keyword co-occurrence map based on bibliographic data. The visualization analysis is shown in Fig. 3. Five clusters in different colors approximately indicate different types of devices. Most obviously, implantable nanogenerator and biofuel cell account for the top two largest proportions. The research focuses of implantable nanogenerator are "piezoelectric", "triboelectric", "nanowires", "in-vivo" and so on [12–14]. At the same time, for the implantable biofuel cell, they are "glucose", "oxidase", "performance", "tissue" and more [15–18]. These high-frequency keywords deliver us what the researchers focus on and what key points should be paid more attention to.

The size of bubbles indicates the citation frequency of publications. The various color of them reflects different clusters [8]. If the items were cited by other identical publications frequently, their space and color would be closer to each other. Furthermore, we coupled the keywords co-occurrence in the map and showed them on the bubbles. The number of keywords co-occurrence corresponds to the size and color of bubbles as well.

There are also some connections among the different clusters. It is mainly because some groups have attempted to combine two or more different devices to test their coupling effect [19]. For example, Hansen et al. presented a hybrid IEH that combined PENG and biofuel cell (glucose/O_2) for concurrently harvesting biomechanical and biochemical energy *in vivo* [20].

Local Citation Score (LCS) is the number of citations for a paper cited by others in the local collection. We can quickly locate the classic literature in a field based on LCS. For example, the local group of implantable nanogenerator has 168 records. 41 of them cited the article "Dagdeviren C et al., 2014, P NATL ACAD SCI USA, V111, P1927" [21]. Therefore, the LCS of it is 41. Sorted by LCS, Top 5 most significant publications of these five types of IEHs are listed in Table 1. The bold part are the devices that have been realized in implantation. Furthermore, the link strength of these publications is also obtained and derived from the citation map based on the bibliographic data by VOSviewer. The link strength is the lines number of bubbles, which reflects the relationship between a publication and others.

3. Analysis of self-powered implantable medical electronics

The published prototypes of SIMEs based on IEHs are listed in Table 2, mainly including cardiac pacemaker, biosensor, nerve stimulation device, wireless communication healthcare system and retinal implant device [22–28]. The number of researches on cardiac pacemaker is the largest, implicating that the energy limitation of it is an emergency problem to be solved. The IEHs could provide some available solutions to it. Since the birth of the first *in vivo* cardiac pacemaker in 1958, its battery life has become one of the most significant challenges [29]. The battery life of a cardiac pacemaker is about 7–10 years. Surgery must be performed when the battery should be replaced, which would increase patient's physical and economic burdens. Therefore, for the research on the power system of cardiac pacemaker, it is very urgent to find an effective solution to prolonging the lifetime of the traditional

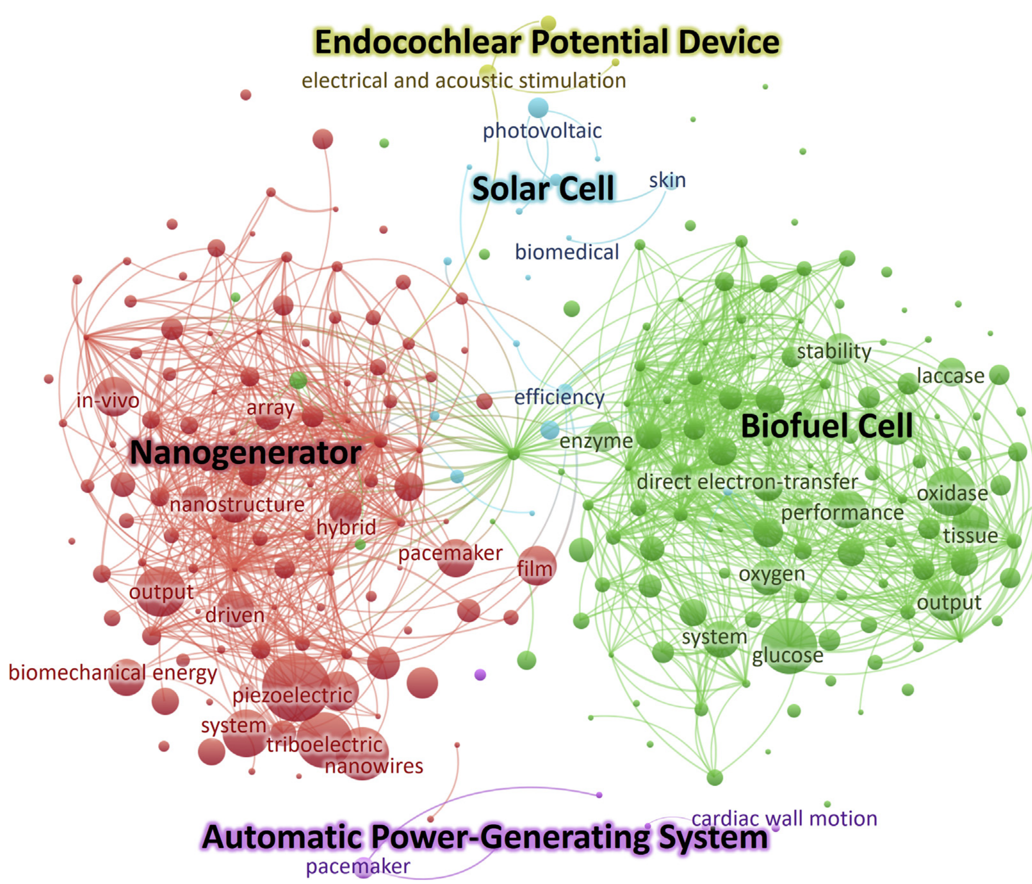

Fig. 3. Citation and keyword co-occurrence map of different IEHs.

Table 1
Top 5 largest Local citation score (LCS) publications of five types of IEHs.

Types	LCS	Link strength	Material	Publication
Nanogenerator	41	44	PZT	**Dagdeviren C et al., 2014, *PNAS*, V111, P1927**
	36	38	Kapton/PET	Fan FR et al., 2012, *Nano Energy*, V1, P328
	33	40	Kapton/Al	**Zheng Q et al., 2014, *Advanced Materials*, V26, P5851**
	31	33	ZnO	Yang RS et al., 2009, *Nature Nanotechnology*, V4, P34
	31	32	ZnO	**Li Z et al. *Advanced Materials*, V22, P2534**
Biofuel Cell	48	48	Enzyme/Electrodes	Mano N et al., 2003, *JACS*, V125, P6588
	48	49		Heller A et al., 2004, *PCCP*, V6, P209
	36	39		**Cinquin P et al., 2010, *PloS One*, V5, e10476**
	35	41		**Halamkova L et al., 2012, *JACS*, V134, P5040**
	28	32		**Rasmussen M et al., 2012, *JACS*, V134, P1458**
Solar Cell	6	6	P^+/N^- well diode arrays	Ayazian S et al., 2012, *IEEE Transactions on Biomedical Circuits and Systems*, V6, P336
	5	5	Si PIN photodiodes	**Goto K et al., 2001, *IEEE Transactions on Biomedical Engineering*, V48, P830**
	4	4	GaInP/GaAs	**Song K et al., 2016, *Advanced Healthcare Materials*, V5, P1572**
	4	4	KXOB22-04X3®, IXYS	**Haeberlin A et al., 2014, *Europace*, V16, P1534**
	3	4	KXOB22-04X3®, IXYS	**Haeberlin A et al., 2015, *Heart Rhythm*, V12, P1317**
Automatic Power-Generating System	3	3	Automatic Wristwatch	**Goto H et al., 1999, *Medical & Biological Engineering & Computing*, V37, P377**
	1	3		**Zurbuchen A et al., 2013, *Annals of Biomedical Engineering*, V41, P131**
	0	3		**Zurbuchen A et al., 2017, *IEEE Transactions on Biomedical Circuits and Systems*, V11, P78**
Endocochlear Potential Device	1	1	Glass Microelectrodes	**Mercier PP et al., 2012, *Nature Biotechnology*, V30, P1240**
	0	1		**Bandyopadhyay S et al., 2014, *IEEE Journal of Solid-State Circuits*, V49, P2812**

Note: The bold part are the devices that have been realized in implantation.

Table 2
Reported prototypes of SIMEs based on IEHs.

Type	Year	GCS	Publication
Cardiac pacemaker	1999	47	Goto H et al., 1999, *Medical & Biological Engineering & Computing*, V37, P377
	2001	74	Goto K et al., 2001, *IEEE Transactions on Biomedical Engineering*, V48, P830
	2010	228	Cinquin P et al., 2010, *PloS One*, V5, e10476
	2010	184	Li Z et al., 2010, *Advanced Materials*, V22, P2534
	2013	77	Castorena-Gonzalez JA et al., 2013, *Electroanalysis*, V25, P1579
	2013	65	Zurbuchen A et al., 2013, *Annals of Biomedical Engineering*, V41, P131
	2014	363	Dagdeviren C et al., 2014, *PNAS*, V111, P1927
	2014	188	Zheng Q et al., 2014, *Advanced Materials*, V26, P5851
	2014	18	Haeberlin A et al., 2014, *Europace*, V16, P1534
	2015	53	Lu BW et al., 2015, *Scientific Reports*, V5,16,065
	2015	27	Haeberlin A et al., 2015, *Heart Rhythm*, V12, P1317
	2016	35	Song K et al., 2016, *Advanced Healthcare Materials*, V5, P1572
	2017	13	Zurbuchen A et al., 2017, *Heart Rhythm*, V14, P294
	2019	21	Ouyang H et al., 2019, *Nature Communications*, V10, 1821
Biosensors	2013	198	Zebda A et al., 2013, *Scientific Reports*, V3, 1516
	2013	46	Andoralov V et al., 2013, *Scientific Reports*, V3, 3270
	2016	83	Ma Y et al., 2016, *Nano Letters*, V16, P6042
	2016	39	Shi BJ et al., 2016, *Advanced Materials*, V28, P846
	2016	32	Cheng XL et al., 2016, *Nano Energy*, V22, P453
	2018	15	Zhang W et al., 2018, *Nano-Micro Letters*, V10, P32
	2019	18	Liu Z et al., 2019, *Advanced Functional Materials*, V29, 1807560
Nerve(Brain) stimulation devices	2015	91	Hwang GT et al., 2015, *Energy & Environmental Science*, V8, P2677
	2016	123	Zheng Q et al., 2016, *Science Advances*, V2, e1501478
	2018	14	Hassani FA et al., 2018, *ACS Nano*, V12, P3487
	2018	14	Yao G, 2018, *Nature Communications*, V9, P5349
Wireless communication healthcare system	2016	91	Zheng Q et al., 2016, *ACS Nano*, V10, P6510
	2017	51	Kim DH et al., 2017, *Advanced Functional Materials*, V27, 1700341
Retinal implant devices	2004	4	Laube T et al., 2004, *Graefes Archive for Clinical and Experimental Ophthalmology*, V242, P661
	2018	3	Wu CY et al., 2018, *Sensors and Materials*, V30, P193

battery or replacing it. That's why there are so many prototypes devices of IEHs for cardiac pacemakers being studied.

It is also a suitable application for IEHs to be served as the power system for biosensors, according to the statistical data. They have relatively high global citation score (GCS) as well. Based on the five types of IEHs, there is a lot of self-powered biosensors have been designed. Zebda et al. demonstrated a single implanted enzymatic cell that can power a digital thermometer, which was operated in a rat for 110 days without any rejection or inflammation [26]. Andoralov et al. constructed a neuronal signal detection device based on biofuel cell consisted of microscale nanostructured electrodes [30]. Ma et al. used implantable triboelectric nanogenerator to monitor heart rates, respiratory rates and estimated blood pressure. The device had been implanted into Yorkshire pigs (male, 30 kg) to illustrate the feasibility [31]. Shi et al. used a hybridized nanogenerator to drive a commercial thermometer [32]. Cheng et al. proposed a self-powered implantable blood pressure monitor based on a piezoelectric thin film [33]. Zhang et al. demonstrate a self-powered implantable skin-like glucometer for real-time detection of blood glucose level *in vivo* [34]. Liu et al. designed an ultrasensitive, miniaturized and self-powered endocardial pressure sensor (SEPS) based on triboelectric nanogenerator (TENG) [35].

4. Separate analyses of implantable nanogenerator

Basically, the complete definition of nanogenerator was presented by Prof. Wang in 2006, which was a piezoelectric nanogenerator (PENG) based on zinc oxide nanowire arrays. The PENG can convert tiny mechanical energy into electricity [36]. Then, Li et al. from the same research group realized implantable nanogenerator in 2010. They have made a single wire nanogenerator based on ZnO nanowire to harvest *in vivo* biomechanical energy from heartbeat and breathing of a live rat. It is the first successful attempt to convert the active biomechanical energy into electricity by nanogenerator [37].

Another crucial headway is TENG demonstrated in 2012, which has caused a surprising change in terms of the research of nanogenerator [38]. In 2014, Zheng et al. realized implantable TENG (iTENG) that was placed into a living rat to harvest energy from the biomechanical motion of respiration [39]. With the inception of iTENG, the researches on implantable nanogenerator have increased sharply since 2014.

It can be summarized from the above analysis that implantable nanogenerator plays an influential role in IEHs and SIMEs, which has gotten a rapid growth during recent decade. A heat map of link relationship about implantable nanogenerator is shown in Fig. 4. Each line represents at least one publication that is completed by two institutions on the two ends of the line. The hottest areas of researches on implantable nanogenerator are East Asia and the United States of America. The top 3 organizations contributed to the number of publications are Georgia Institute of Technology, Chinese Academy of Sciences and Korea Advanced Institute of Science and Technology. If we do statistics by considering national contributions, China followed by South Korea and the United States is the country with the largest number of publications.

The result of citations in a same field can locate important papers. Fig. 5 shows established citation relationship among nanogenerators that have been realized in implantations. Each bubble represents one paper. And the size of these bubbles represents the number of citations. The larger size of the bubble, the more times the paper is cited. Furthermore, each line represents a citation relationship. The change in color from purple to red implies the span of time.

As mentioned above, the first implanted nanogenerator was published in 2010 [37]. It is the first time that demonstrated the feasibility of implantable nanogenerator to collect *in vivo* mechanical energy from animals and proved that nanogenerator can be used in SIMEs. In 2014, the first iTENG has been presented to be implanted to harvest energy from biomechanical motion of living organisms [39]. At the same year, Dagdeviren et al. implanted piezoelectric device into bovine and ovine to harvest the energy generated by heartbeat and breathing [21]. These three works play essential roles in the fields of IEHs and SIMEs. They are generally almost the beacons for this field. Li et al. realized the first step to make implantable nanogenerator from theory to reality. And they have been working on this work since then. Recently, they have reported a symbiotic cardiac pacemaker based on iTENG, which is a breakthrough of self-powered cardiac pacemaker [40]. Until now, their research group is one of the best groups in the field of implantable nanogenerator. Lately, Hinchet et al. reported a significant breakthrough that was published in the Journal of Science. They proposed a new device based on triboelectric device *in vivo* to harvest the ultrasound mechanical energy from *in vitro* and liquid environment effectively, which can recharge the lithium-ion battery (0.7 mAh) to 4.1 V in 4.5 h by the device [41,42].

We list the top 10 journals that published papers about implanted nanogenerator by weighing the LCS factors as shown in Table 3. It implies that implantable nanogenerator has been gaining more and more academic recognition and attention.

5. Five major fields of implantable energy harvesters

IEHs and SIMEs have emerged in the research fields of biomedical engineering, energy science, material science, electronic technique and interdisciplinary areas during last decades [43,44]. By summarizing and analyzing the data from WOS, we classify five major types of IEHs and some representative SIMEs based on IEHs (Fig. 6), which have been realized in implantations in animal testing. These analysis results show the potential of using IEHs and SIMEs for further clinical applications [45,46]. In particular, such devices are subjects of intense interest of application in

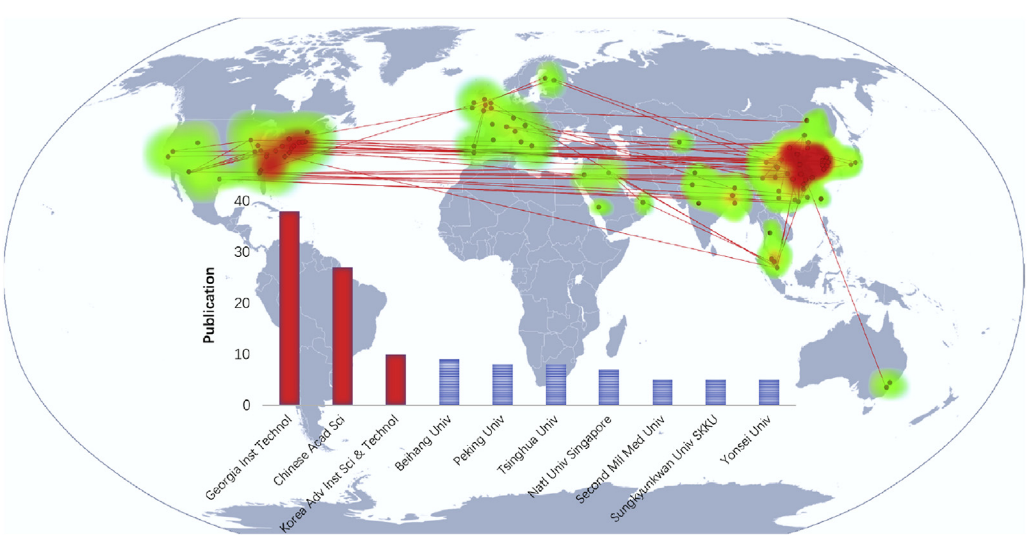

Fig. 4. Cooperation between regions of relevant publications on implantable nanogenerator.

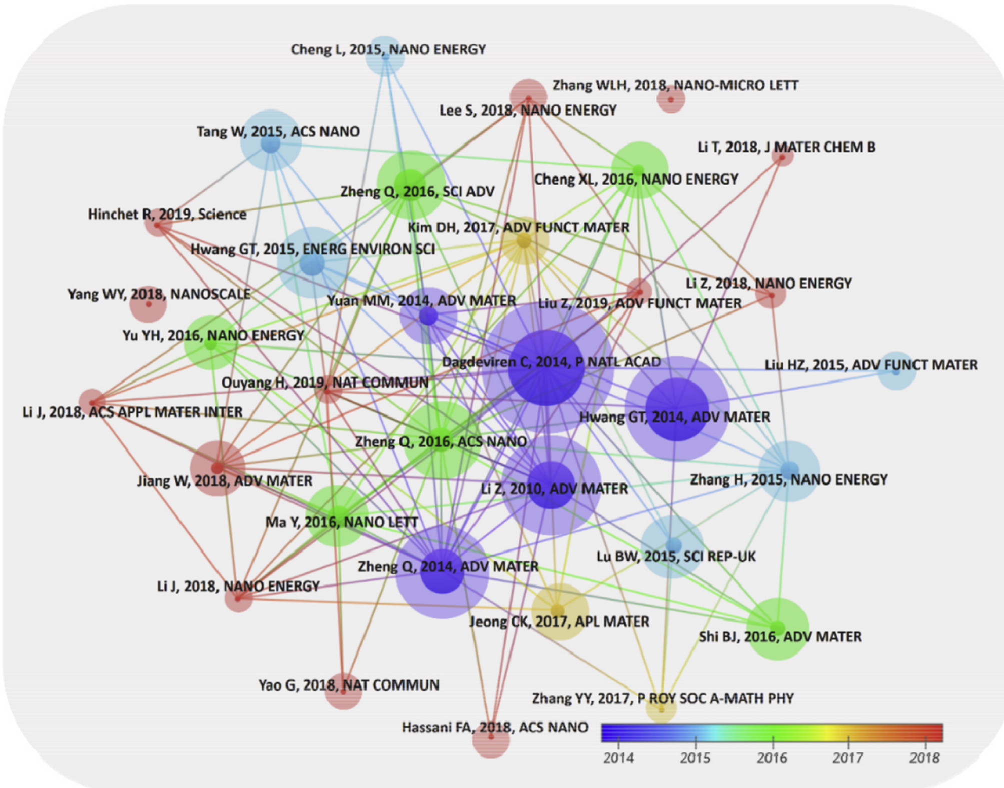

Fig. 5. Citation map among implanted nanogenerator based on bibliographic data.

cardiac pacemaker by delivering power harvested from abundant mechanical, chemical or optical energy.

6. Challenges and prospects

According to the bibliometric and visualization analyses, we deliver accurate and visual results to the researchers who are interested in the field of IEHs and SIMEs. As summarized above, for clinical applications, the proportions of nanogenerator and biofuel cell are higher than that of automatic power-generating system, solar cell and endocochlear potential devices. Considering that implantable nanogenerator has an impressive rapid development, we analyze the evolutionary trend of it separately. There are two key findings in the development of implantable nanogenerator: One is the first implanted piezoelectric nanogenerator was reported in 2010, and the other one is the first implanted triboelectric nanogenerator was reported in 2014. Later, a boom of research about SIMEs based on implantable nanogenerator has arrived, such as symbiotic cardiac pacemaker and real-time self-powered biomedical monitoring sensor. Meanwhile, we suggest that the challenges and research emphases of IEHs and SIMEs in the future mainly include three aspects as follows:

(1) **Long-term *in vivo* evaluation.** One of the targets of IEHs and SIMEs is to achieve implant for life, thus the long-term durability and biocompatibility *in vivo* are key important issues. Although, some recent IEHs and SIMEs have been tested *in vivo* in animal experiments, few of them reach a living implantation more than one year. It is not certain that whether the long-term implantation would cause side effects such as inflammation, unknown toxicity of tiny precipitates from the devices and potential risk of influencing normal organ function like hear beating or respiration. It will take a long time to complete the *in vivo* evaluation criteria of biocompatibility of these devices, before implanting the IEHs and SIMEs into human body.

(2) **Minimally invasive surgery for implantations.** No matter to harvest energy from heartbeat or blood sugar, these IEHs and related SIMEs must be both implanted into body through surgeries. The development of minimally invasive operation such as interventional cardiac catheterization that are often used in pacemaker implantation may provide an appropriate solution for implantation of IEHs and SIMEs. To meet the requirements of the minimally invasive surgery, the size, the flexibility and the operability of the devices should be considered as a major concern. Meanwhile, some IEHs which are placed underneath the skin for absorbing transmitted energy from tailor-made power source, like ultrasound and light. These devices can be implanted by a minor surgery. The

Table 3
Top 10 journals that published papers about implanted nanogenerator.

Journal	LCS	GCS	IF	Records
Advanced Materials	46	511	25.809	5
Acs Nano	26	165	13.903	3
Nano Energy	22	194	15.548	7
PNAS	20	354	9.58	1
Science Advances	8	123	12.804	1
Nano Letters	6	81	12.279	1
Energy & Environmental Science	4	90	33.25	1
Advanced Functional Materials	2	110	15.621	4
Scientific Reports	2	49	4.011	1
Nature Communications	1	38	11.878	2
Science	0	8	41.037	1

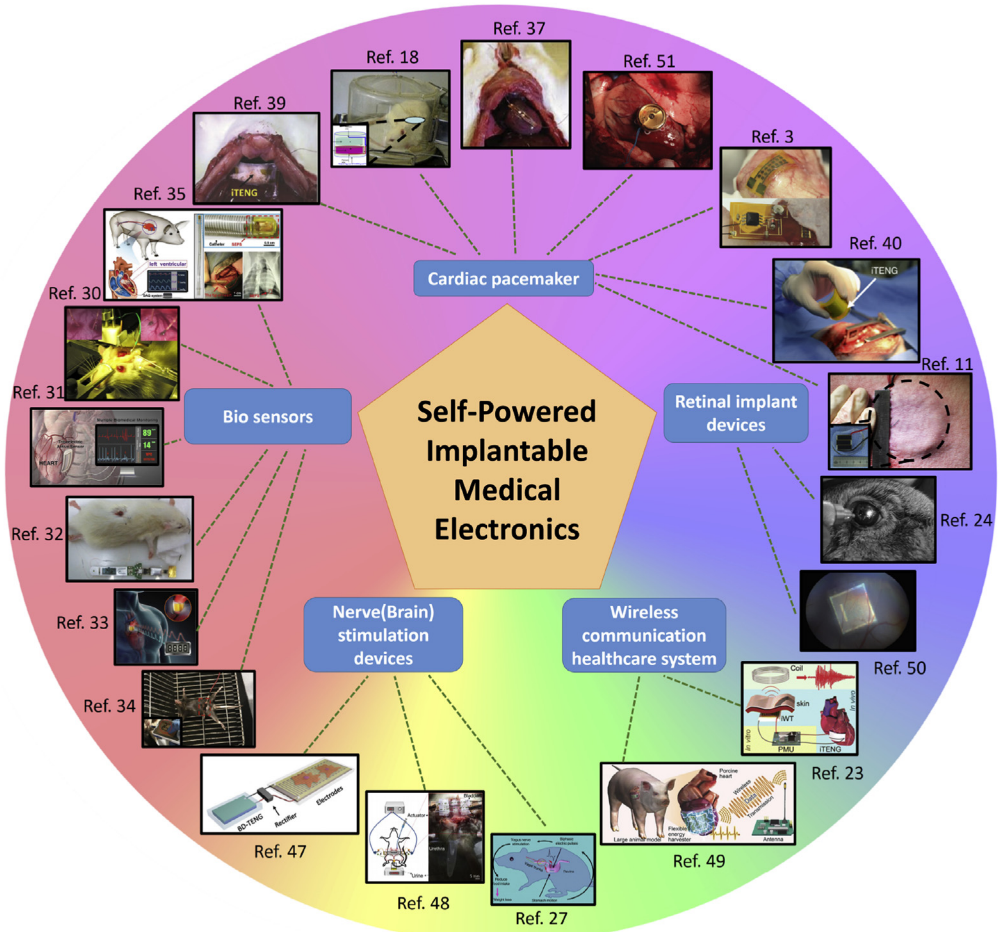

Fig. 6. Summary of recent five major fields of IEHs: serving for cardiac pacemakers, biosensors, nerve (brain) stimulation devices, wireless communication healthcare systems and retinal implants. Reproduced with permissions: Ref. [37], copyright 2010 Wiley-VCH. Ref. [18], copyright 2010 PLOS. Ref. [39], copyright 2014 Wiley-VCH. Ref. [35], copyright 2018 Wiley-VCH. Ref. [30], copyright 2013 Springer Nature. Ref. [31], copyright 2016 American Chemical Society. Ref. [32], copyright 2015 Wiley-VCH. Ref. [33], copyright 2016 Elsevier. Ref. [34], copyright 2018 Springer Nature. Ref. [47], copyright 2016 American Association for the Advancement of Science. Ref. [48], copyright 2018 Springer Nature. Ref. [27], copyright 2018 American Chemical Society. Ref. [49], copyright 2017 Wiley-VCH. Ref. [23], copyright 2016 American Chemical Society. Ref. [50], copyright 2017 MYU K.K. Ref. [24], copyright 2004 Springer-Verlag. Ref. [11], copyright 2014 Oxford University Press. Ref. [40], copyright 2019 Springer Nature. Ref. [3], copyright 2016 Wiley-VCH. Ref. [51], copyright 2012 Biomedical Engineering Society.

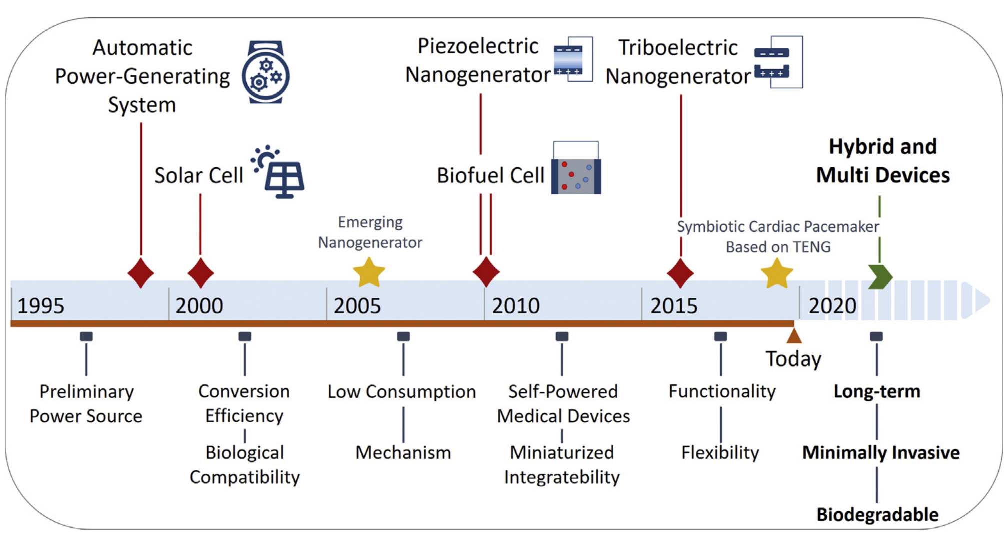

Fig. 7. Retrospect and prospect of IEHs and SIMEs.

subcutaneous IEHs implanted by minimally invasive surgery would be another interesting and practical thoughts for the future [52].

(3) **Bioresorbable devices.** Although, most of the IEHs and SIMEs need to be implanted for a long time, there are still requirements for retrieving the device through a secondary surgery, such as devices for drug delivery, wound healing and nerve repair [53–55]. Due to the advance of biodegradable materials, implantable transient medical devices and bioresorbable electronics have achieved increasing attention recently. Researchers also developed bioresorbable IEHs based on natural materials like silk fibroin, cellulose and chitin. However, bioresorbable IEHs is not enough. It is the key approach to realize the biodegradable IEHs based functional devices or systems, ultimately, to build up a highly integrated fully bioresorbable SIMEs. For this purpose, lots of techniques including bioresorbable electron components, circuit and method for controlled degradation have to be settled urgently.

The retrospect and prospect of IEHs and SIMEs are shown in Fig. 7. The research focus in each interval and the future perspective have been summarized. Hybrid and multifunctional devices might become mainstream in the fields, which can harvest energy through various approaches including piezoelectric, triboelectric, biofuel, electromagnetic, even harvesting energy from *in vivo* and *in vitro* synchronously. The emergence of IEHs and SIMEs represents a great paradigm shift in future implantable medical electronics for human-integrated fields, which means these devices could extract energy from human body to prolong their life span, even implant for life. This bibliometric study might provide some fresh and useful references for the development of implantable energy harvesting techniques and self-powered medical electronics.

Declaration of interests

The authors declare no conflict of interest.

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