

Fifty Years of Innovation in Plastic Surgery

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Background Innovation has molded the current landscape of plastic surgery. However, documentation of this process only exists scattered throughout the literature as individual articles. The few attempts made to profile innovation in plastic surgery have been narrative, and therefore qualitative and inherently biased. Through the implementation of a novel innovation metric, this work aims to identify and characterise the most prevalent innovations in plastic surgery over the last 50 years.

Methods Patents and publications related to plastic surgery (1960 to 2010) were retrieved from patent and MEDLINE databases, respectively. The most active patent codes were identified and grouped into technology areas, which were subsequently plotted graphically against publication data. Expert-derived technologies outside of the top performing patents areas were additionally explored.

Results Between 1960 and 2010, 4,651 patents and 43,118 publications related to plastic surgery were identified. The most active patent codes were grouped under reconstructive prostheses, implants, instruments, non-invasive techniques, and tissue engineering. Of these areas and other expert-derived technologies, those currently undergoing growth include surgical instruments, implants, non-invasive practices, transplantation and breast surgery. Innovations related to microvascular surgery, liposuction, tissue engineering, lasers and prostheses have all plateaued.

Conclusions The application of a novel metric for evaluating innovation quantitatively outlines the natural history of technologies fundamental to the evolution of plastic surgery. Analysis of current innovation trends provides some insight into which technology domains are the most active.

Keywords Surgery, plastic / Technology / Diffusion of innovation / History

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INTRODUCTION

Healthcare innovation has shaped the evolution of plastic surgery in the last century. Perhaps the most historic demonstration of such was the pioneering work of Sirs Harold Gillies and Archibald McIndoe in the World Wars of 1914 and 1939 [1,2]. Since then, both invention and implementation of new technologies have continued to facilitate advances in patient outcomes

and opportunities in plastic surgery.

Outside of the healthcare literature, the study of the process of innovation (i.e., diffusion of innovation) is a mature field originating from the observations of social scientists in the mid-twentieth century [3,4]. Patents and publications are well-documented measures of innovation and exist in vast numbers detailing technological advances in surgery. Although articles exist in the healthcare literature relating to the diffusion of innovation, many

focus on healthcare processes with few offering an objective or quantitative view of the diffusion of technological innovation [5].

Key plastic surgical innovations, in the context of both research and clinical medicine, listed in the literature include microsurgery, breast surgery, liposuction, tissue engineering, transplantation, and laser technology [6,7]. These suggestions were made on the basis of significant professional experience, but a distinct lack of evidence. Recent work has demonstrated the utility of publically available patent and publication data to quantify innovation within surgery and proposes a novel methodology for assessing areas of technological innovation [8-10].

Such systematic approaches to horizon scanning for new evidence of innovation poses significant opportunities and implications within research-funding bodies and investors alike. Current strategies for directing the nature of calls for proposals, as well as choosing those that are supported, might be more reliably guided by more robust technology trend analyses. Furthermore, reviewing these historical data might better inform academic programmes when appraising and advancing research angles.

The objectives of this paper are: first, to identify and characterise the most prevalent areas of innovation in plastic surgery using patent and publication data; and second, to evaluate key areas of innovation outlined by experts in the literature.

METHODS

Patent and publication data retrieval

Patents from over 90 countries and publications for plastic surgery between 1960 and 2010 were retrieved using the proprietary software *PatentInspiration* (Aulive, Ypres, Belgium) and Pub-

Med (National Library of Medicine, Bethesda, MD, USA). The Boolean search strategy (“plastic surgery” OR “plastic surgeon” OR “plastic surgical”) was used, limiting the results to single members of patent families in order to prevent duplication. Data for patent and publication activity were normalised using an innovation index as described by Hughes-Hallett et al. [8]. The innovation index is calculated by dividing the number of publications or patents in a given year by the total patent and publication counts from 2010 (‘present day’). This has the effect of highlighting change in activity beyond that caused by natural growth in industry and the population.

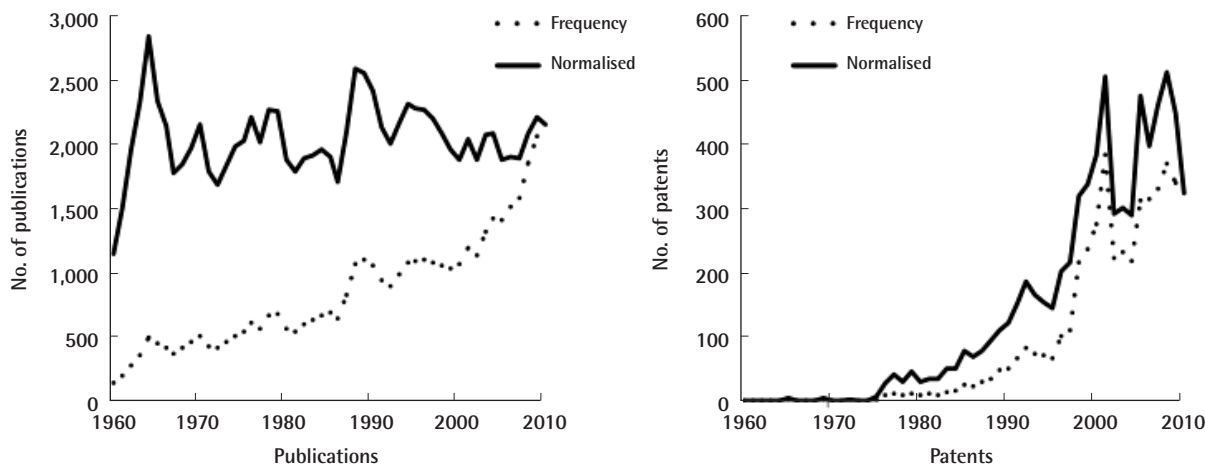
Top performing patent codes

Every patent filed is classified using one or more standardised hierarchical codes, e.g., ‘A61F2/12’ for Mammary prostheses and implants. The 50 most prevalent patent codes associated with the technologies retrieved from the database search were identified and grouped under subheadings chosen by the authors. Assignment of codes into technology areas was conducted independently by 2 authors (R.M.K. and H.J.M.), with any disagreement being resolved by a third (A.H.H.). Patents related to pharmaceutical products were omitted. This process was repeated each decade to explore change over time.

The activity of the top performing technology areas was investigated further through specific searches of patents and publications. Search terms were built and modified to minimise the appearance of unwanted results on a case-by-case basis. For example, in cases where search terms might be considered generic, such as ‘device’, patent searches were limited to results in which the term was present in the title or abstract. Normalised data

Fig. 1. Publication and patent activity in plastic surgery

After data normalisation with respect to total publications or patents filed (all fields), the publication activity appears to be steady, whereas patent activity is exhibiting an exponential rise.



were plotted graphically to facilitate the assessment of growth patterns. To account for smaller datasets related to specific technologies, moving averages were employed in order to ease interpretation.

Expert-derived technologies

A further series of searches was conducted to investigate expert-derived specific areas of interest highlighted in 2 publications [6,7], which were vulnerable to absorption by generic technology subheadings in the initial search strategy.

Statistical analysis

Evidence suggests that a high correlation between patents and

publications during periods of growth is indicative of substantial innovation [11]; therefore, correlation coefficients were calculated. In the case of a monotonic relationship, Pearson's or Spearman's rank was used for linear or non-linear associations, respectively. The coefficient of determination (R^2) was used to quantify and compare the fit of data to linear and exponential trend lines. Statistical analysis was performed using the IBM SPSS ver. 19.0 (IBM Co., Armonk, NY, USA).

RESULTS

In plastic surgery between 1960 and 2010, 4,651 patents and 43,118 publications were retrieved. After normalisation, the pub-

Table 1. Hierarchy of top 50 performing patent codes in plastic surgery between 1960 and 2010 (omitting pharmaceutical products)

Code	Frequency	Code description
Reconstructive prostheses		
A61L27/227	135	Polypeptide macromolecular materials for prostheses or coating prostheses
A61L27/56	125	Porous materials for prostheses or coating prostheses
A61L27/24	113	Collagen materials for prostheses or coating prostheses
A61L27/18	111	Macromolecular materials (non C-C unsat bonds) for prostheses or coating
A61L27/54	108	Biologically active materials for prostheses or coating
A61L2430/02	105	Materials or treatment for tissue regeneration - bones and weight-bearing implants
A61L27/34	104	Macromolecular materials for coating prostheses
A61L27/50	95	Material characterised by their function or physical properties for prostheses or coating prostheses
A61L27/52	89	Hydrogel materials for prostheses or coating prostheses
A61F2310/00365	88	Proteins for prostheses
A61L27/3608	87	Bony prostheses
A61F2210/0004	83	Bioabsorbable materials for prostheses
A61L27/58	77	Partially resorbable materials for prostheses or coating prostheses
A61F2/28	77	Bony implants or prostheses
A61L27/3683	74	Pre-implantation treated prostheses
A61L27/16	68	Macromolecular materials (involving C-C unsat bonds) for prostheses or coating
A61F2002/30062	67	Bioabsorbable materials for joint prostheses
A61L27/12	67	Phosphorus-containing materials (e.g. apatite) for prostheses or coating prostheses
	1,676	
Implants		
A61F2/12	198	Mammary prostheses and implants
A61F2/0059	106	Cosmetic or alloplastic implants
	304	
Instruments		
A61B2018/00452	98	Surgical instruments for the skin
A61B17/06166	79	Sutures
A61B2017/00792	75	Instruments for plastic surgery
A61B19/24	71	Devices for expanding tissue
	323	
Non-invasive		
A61Q19/08	167	Anti-ageing preparations for the skin
A61Q19/00	160	Preparations for care of the skin
A61K9/0024	102	Solid, semi-solid or solidifying implants (injectables)
A61B18/203	82	Applying laser energy to the outside of the body
	511	
Tissue engineering		
A61L27/60	80	Materials used in artificial skin
A61L27/3804	70	Transplanted living cells
	149	
Miscellaneous		
G06Q50/22	77	Patient record management

lication activity appeared to be steady, whereas patent activity exhibited an exponential rise (R^2 exponential = 0.85) (Fig. 1).

Between 1960 and 2010, the top performing technology groups were reconstructive prostheses, non-invasive practices, surgical instruments, implants, and tissue engineering (Table 1).

Technologies related to surgical instruments were the most active in terms of patent filing in the 1980's. In the last two decades, patents related to reconstructive prostheses have become the most prevalent, with instruments and non-invasive techniques comprising the majority of the remaining technologies (Table 2). Patents related to pharmaceutical products were omitted (1980's, 8; 1990's, 16; 2000's, 17; 1960–2010, 19).

Of the top performing technology areas (Table 3), instruments, non-invasive technologies and tissue engineering all have strong correlations between patent and publication activity (range Spearman's rank, 0.678–0.893; $P < 0.001$). Implants, instruments and non-invasive technologies all appear to be undergoing growth, whilst reconstructive prostheses and tissue engineering have shown convincing plateaus. Of the growing technologies, instruments and non-invasive technologies both show greater concor-

dance with exponential lines of best fit (average exponential vs. linear $R^2 = 0.8$ vs. 0.7), whilst implants rise in a more linear fashion ($R^2 = 0.6$ vs. 0.7) (Fig. 2).

Microsurgery (within plastic surgery) accounted for 156 patents, following a sigmoidal growth curve plateauing in 2000. Breast surgery (109 patents) appeared to exhibit potentially two distinct growth phases—first in the 1980's and again in the late 2000's. Liposuction (34) underwent rapid growth almost immediately on conception in the late 1980's, which was unsustainable. Tissue engineering (403) and laser technologies (104) both exhibited sigmoidal growth curves with plateaus in the mid- and early 2000's, respectively. Patents related to transplantation (649) display a dramatic exponential growth phase around the year 2000, which is only very recently showing signs of cessation. Of the growing technologies, transplantation was strongly exponential (exponential vs. linear $R^2 = 0.7$ vs. 0.3), whereas breast surgery was mostly exponential ($R^2 = 0.5$ vs. 0.4) in its growth trend. The correlations between patents and publications were all statistically significant, with all apart from breast being strong ($R > 0.7$) (Fig. 3).

Table 2. Number and distribution of patents over time

Variable	1980's	1990's	2000's	1960–2010
Patent code frequency (%)				
Reconstructive prostheses	163 (28)	775 (61)	687 (38)	1,676 (55)
Implants	102 (18)	100 (8)	112 (6)	304 (10)
Instruments	229 (40)	89 (7)	421 (24)	323 (11)
Non-invasive	36 (6)	192 (15)	366 (20)	511 (17)
Tissue engineering	22 (4)	115 (9)	90 (0.5)	149 (5)
Total patents (including miscellaneous)	575	1,271	1,788	3,040

Separate patent searches were conducted for each time period. Patent numbers in the top 5 technology clusters between 1980–2010 surpass those in 1960–2010 as there were more top ranking pharmaceutical patent codes and therefore more patents omitted. Each column (time period) must therefore be considered independently.

DISCUSSION

A novel innovation metric was applied to the field of plastic surgery showing exponential growth in patents over the last 50 years, with a relatively fixed related publication output. This is an expected finding, considering that healthcare patents are outperforming patents in general (the latter of which were used for normalisation). The top performing patent codes, and therefore areas of innovation, were identified as reconstructive prostheses, tissue engineering, implants, instruments, and non-invasive techniques, of which the latter 3 are currently in growth. Expert-derived innovation areas were also evaluated, highlighting the differences (and similarities) between different technologies with

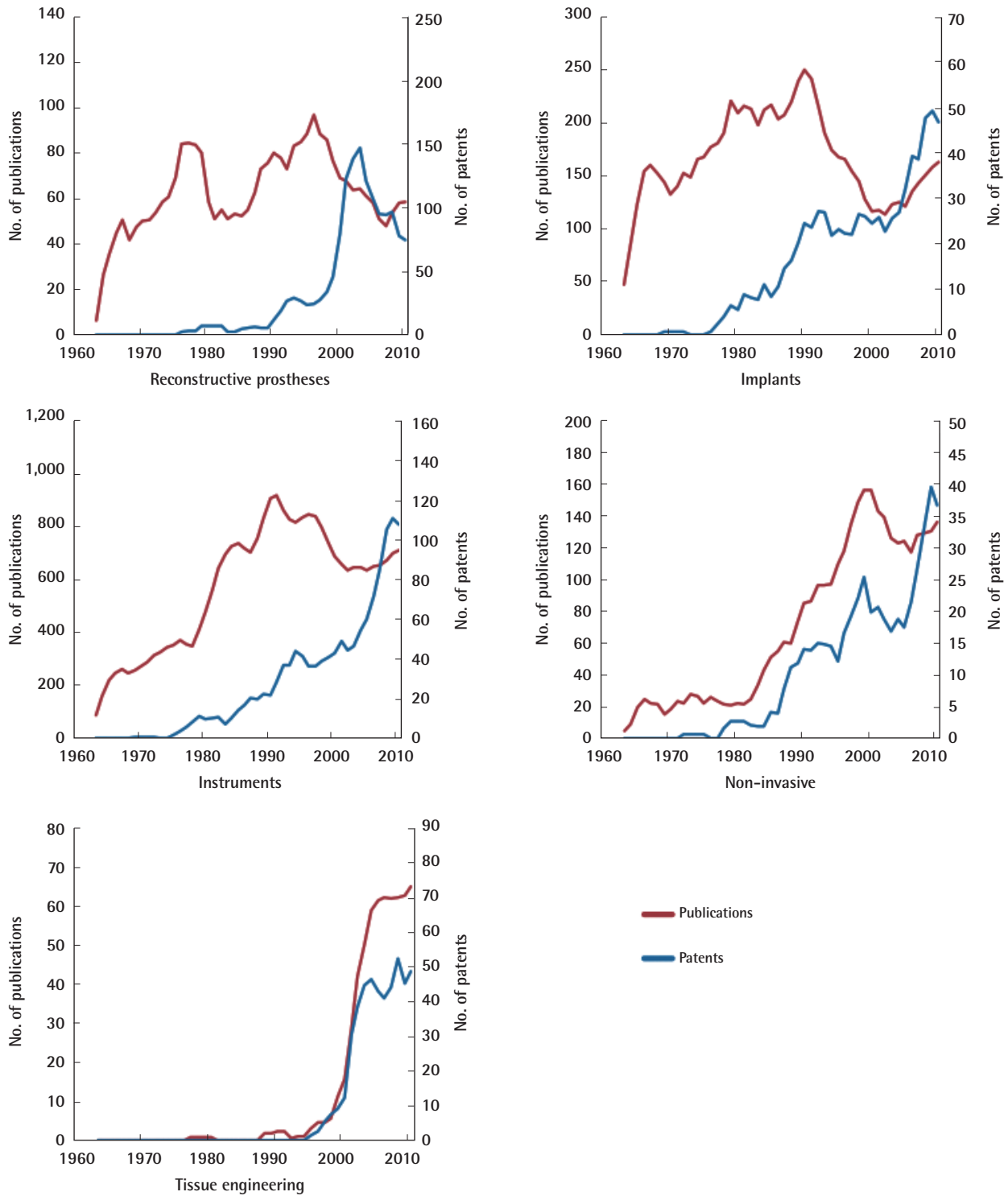
Table 3. Search strategies

Technology	Search strategy
Top performing	
Reconstructive prostheses	(Prosthetic or prosthesis or prostheses) and (bone or joint) and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Implants	(Implant or prosthetic or prosthesis or prostheses) not (bone or joint) and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Instruments	(Instrument or tool or device)* and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Non-invasive	(Laser or injectable or thermal)* and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Tissue engineering	("Tissue engineering") and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Expert-derived	
Microsurgery	(Microsurgery or microsurgical) and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Breast surgery	Breast* and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Liposuction	(Liposuction or lipoplasty or liposculpture or lipectomy)* and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Transplant	(Allotransplant or allograft) and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Tissue engineering	"Tissue engineering" and ("plastic surgery" or "plastic surgeon" or "plastic surgical")
Laser	Laser* and ("plastic surgery" or "plastic surgeon" or "plastic surgical")

*Patent search restricted to title or abstract.

Fig. 2. Top performing patent codes in plastic surgery

This figure shows the normalised publication and patent trends for the 5 top performing (i.e., most prevalent) overarching patent codes. The trends were assessed statistically for correlation between publications and patents, current growth, and exponential growth (as described in the text).



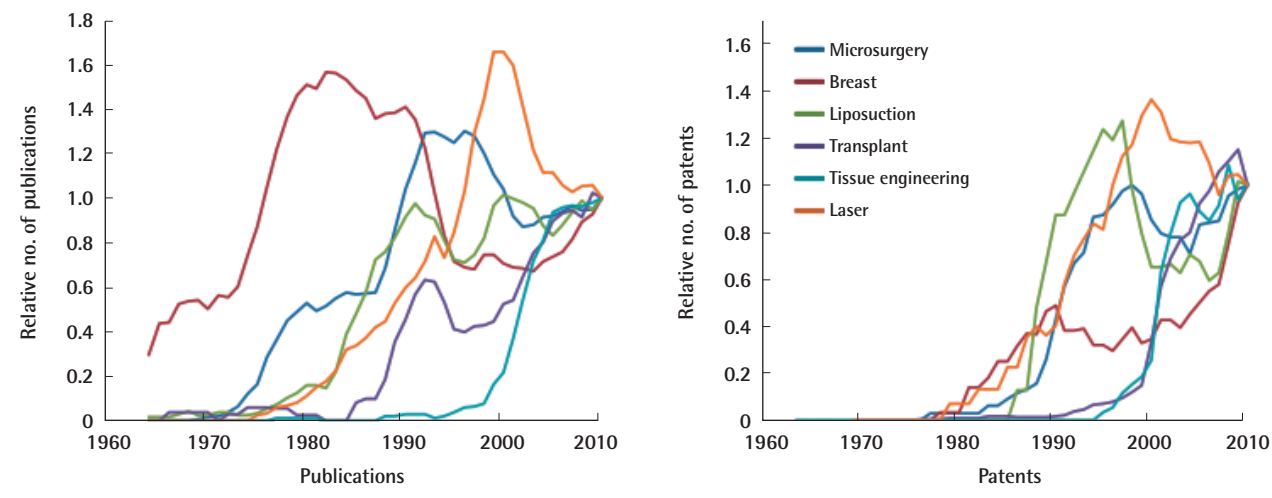
respect to time of conception, growth patterns, and the current state of flux.

The Diffusion of Innovation theory described by Rogers pro-

poses that the technology adoption curve is sigmoidal, with a period of incubation prior to widespread adoption, followed by technological refinement [3]. The data displayed in this work

Fig. 3. Publication and patent activity in expert-derived technologies

This figure compares different areas of innovation as selected by senior plastic surgeons. The normalised data have also been adjusted relative to each area, that is, yearly values divided by technology-specific 2010 values, and therefore trends rather than quantitative data may be compared. The publication and patent trends correlated strongly, and it is apparent that some technologies are currently undergoing growth whilst others have plateaued or are in a static or slump phase.



facilitates guided speculation with regard to forecasting future areas of growth by establishing the current phase of innovation in a particular technology. Technologies currently experiencing growth include surgical instruments, implants, non-invasive techniques, transplantation, and breast surgery. Of these technologies, transplantation is visually and statistically the most exponential, with a concurrent boom in associated publication activity. This is in keeping with the current interest in vascularised composite allotransplantation, both from expanding case series (including the first hand transplant in the UK in 2013) [12,13] and novel strategies for inducing immune tolerance [14,15] that address the ethical constraints associated with long-term immunosuppression [16].

The correlation between publications and patents of the majority of the technology groups were strong, suggesting substantial innovation. However, patents and publications for reconstructive prostheses and implants were poorly correlated. Publication activity in these areas emerges rapidly in the 1960's before plateauing, whereas patents activity rises later on with little impact on publication activity. A poor correlation between publications and patents has previously been explained by periods of technology refinement, where mature technologies are incrementally refined by industry to maintain market share, rather than to modify clinical practice [11].

The majority of innovations listed by senior plastic surgeons were reassuringly represented in the top performing patent codes. Overarching technology areas are likely to envelop niche patents, such as liposuction and negative pressure dressings falling under instruments, for example. Simple and useful technologies

such as liposuction exhibit rapid uptake with a befitting exponential rise, before falling away as the limited number of plausible amendments or advances are exhausted.

Microsurgery is undoubtedly one of the most disruptive innovations in plastic surgery [17]. After Jacobson and Suarez achieved the first experimental microvascular anastomosis using an operating microscope in 1960 [18], a prolonged incubation phase saw various microsurgical cases documented, such as the first arm replant in 1964 [19]. It was only after the assembly of the International Society of Reconstructive Microsurgery in 1972 that the technique began to be more widely adopted, with a subsequent surge in patent activity.

The patent activity of half the technologies explored has plateaued. It is possible that other emerging innovations in plastic surgery have been missed. It is also likely that innovation is occurring in other surgical specialties, to be adopted by plastic surgeons in due course. Hughes-Hallett listed the key areas of innovation in surgery as minimally invasive surgery, robotic surgery, surgical staplers, and image guidance, with robotics and image guidance very much in the exponential phase of growth [8]. Use of robotic platforms for microvascular anastomosis or neurorrhaphy [20], imaging for locating perforating blood vessels [21], and planning surgical reconstruction [22] are beginning to be described in the plastic surgical literature.

Amongst other interesting findings, patient record management was the top performing plastic surgery patent in the 2000's (aside from skin preparations). Similarly, this decade sees the emergence of the patent code for software for market research and analysis. This suggests that the focus of innovation is ex-

panding to address more holistic aspects of the healthcare process, including managing and extracting information from so-called 'big data' to optimise care pathways whilst maintaining a robust healthcare business model.

Although the methodology used provides new insight into innovation in plastic surgery, it is not without limitations. As with systematic reviews, building search terms is an inherent source of bias. To minimise bias, search terms were kept concise, avoiding listing specific technologies to add to or limit the search where possible. Also, the same search terms were used for patents and publications, regardless of differences in article architecture. Additionally, the results generated from nonspecific patent search terms such as 'device' were restricted to those found in the title or abstract and not the description, which can often include a broader discussion of technology components not central to the innovation in focus in the patent.

Reconstructive prostheses comprise a large industry, which spans multiple specialties. Whilst such technology may be more typically associated with orthopaedics, the wide applicability and the format of the patent applications result in it being a major feature in this study. Plastic surgery is unique in that the specialty is not confined to a single organ or organ system, which makes defining a search strategy more challenging. The study methodology was more likely to be overly inclusive rather than incomplete, as any technology that may be encountered by a plastic surgeon is likely to be listed in the patent application.

Furthermore, patent records are such that any patent may fall under more than 1 code, potentially leading to over-representation of a particular patent when assessing the top performing patent areas. It is conceivable that this phenomenon is skewed towards certain technology areas, for example a new multi-modular hip prosthesis with a smart coating may result in 5 or more 'hits' on various prosthesis-related patent codes (Table 1), whereas a breast implant has fewer possibilities. Conducting patent searches using expert-derived technologies in addition to those representing top performing patent codes ensures areas of interest are not disregarded.

The application of a novel metric for evaluating innovation in plastic surgery generated a natural history of technologies fundamental to the evolution of the specialty. This methodology has revealed which technologies are currently undergoing growth, providing unique insight into the expected landscape of clinical and academic plastic surgery in the decades to come. Future work may look to advance the methodology in order to detect the features of emerging technology groups that may be able to predict uptake and ultimately success. Learning from historical trends in patents and publications, along with additional supplementary metrics, might allow the most promising 'seedlings' to

be selected and nurtured through direct resource allocation. This method has the potential to fast track the development and translation of new disruptive technologies into the healthcare domain.

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