From Leonardo to da Vinci: the history of robot-assisted surgery in urology

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The evolution of robots in general and as platforms to augment surgical practice is an intriguing story that spans cultures, continents and centuries. A timeline from Yan Shi (1023–957 bc), Archytas of Tarentum (400 bc), Aristotle (322 bc), Heron of Alexandria (10–70 ad), Leonardo da Vinci (1495), the Industrial Revolution (1790), 'telepresence' (1950) and to the da Vinci® Surgical System (1999), shows the incredible depth of history and development that underpins the modern surgical robot we use to treat our patients. Robot-assisted surgery is now well-established in Urology and although not currently regarded as a 'gold standard' approach for any urological procedure, it is being increasingly used for index operations of the prostate, kidney and bladder. We perceive that robotic evolution will continue infinitely, securing the place of robots in the history of Urological surgery. Herein, we detail the history of robots in general, in surgery and in Urology, highlighting the current place of robot-assisted surgery in radical prostatectomy, partial nephrectomy, pyeloplasty and radical cystectomy.

What's known on the subject? and What does the study add?

Numerous urological procedures can now be performed with robotic assistance. Though not definitely proven to be superior to conventional laparoscopy or traditional open surgery in the setting of a randomised trial, in experienced centres robot-assisted surgery allows for excellent surgical outcomes and is a valuable tool to augment modern surgical practice.

Our review highlights the depth of history that underpins the robotic surgical platform we utilise today, whilst also detailing the current place of robot-assisted surgery in urology in 2011.

KEYWORDS

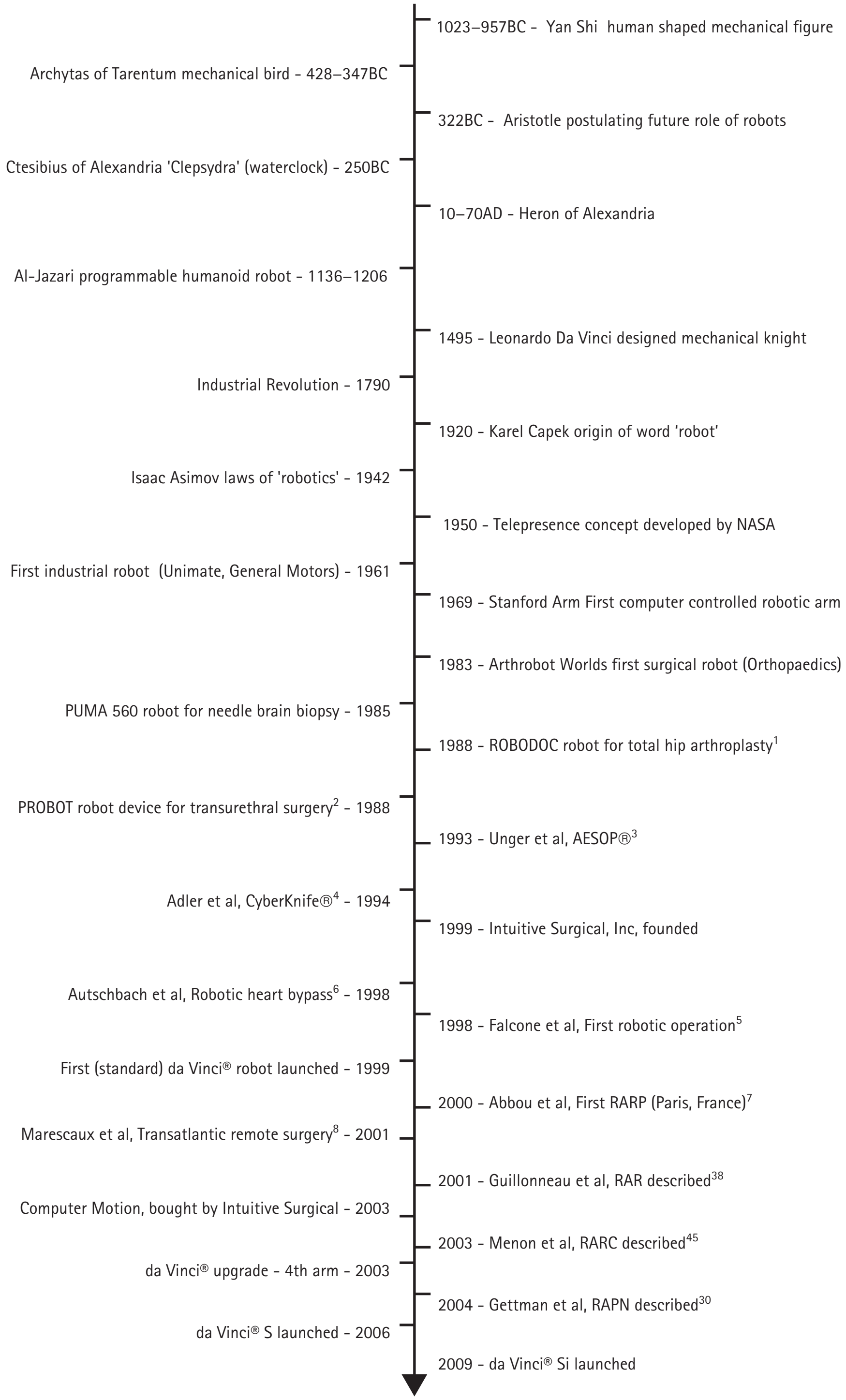
robotics, da Vinci, history, urology, review

HISTORY OF ROBOTS

Etymology of the word 'robot' is relevantly recent in the timeline of so-called 'robots' (Fig. 1 [18,30,38,45]). 'Robota' is the Czech word for compulsory work or forced labour and it was a term used to describe artificial people (roboti) in a 1920s Czech play entitled 'R.U.R: Rossum's Universal Robots' written by Karel Capek. 'Robotics' describes the field of study of robots and is a phrase that was first coined in 1942 by science fiction writer, Isaac Asimov. However, the story of robots begins many hundreds of years previous to this and it is an intriguing story that spans cultures, continents and centuries. In ancient China (1023–957 bc), an 'artificer' (mechanical engineer) called Yan Shi, presented King Mu of Zhou with a life-size, human-shaped mechanical figure. In the 4th century bc (428–347 bc), the Greek mathematician Archytas of Tarentum designed a mechanical bird ('the pigeon'), which was propelled by steam. Further automatons were described in Alexandria, a onetime Roman province of Ptolemaic Egypt. The 'clepsydra', a water-clock with moveable figures on it, was made by physicist and inventor Ctesibius of Alexandria (250 bc) and Heron of Alexandria (10–70 ad) made numerous innovations in the field of automata, including one that allegedly could speak. The famous Greek philosopher Aristotle, referencing Homers Iliad, profoundly speculated in his 'Politics' book (Part 4, 322 bc) that 'if every tool, when ordered, or even of its own accord, could do the work that befits it then there would be no need either of apprentices for the master workers or of slaves for the lords'. Al-Jazari (1136–1206), an Arab Muslim inventor, designed and constructed several automatic machines and the first programmable humanoid robot, a robotic boat with automated musicians used to entertain guests at royal drinking parties. Interest in automata was largely non-existent in medieval Europe but the reason why today we refer to the 'da Vinci® robot' are the seminal recorded designs of a humanoid robot made by the genius Italian sculptor, painter, architect, engineer, anatomist and mathematician, Leonardo Da Vinci circa 1495. Da Vinci's notebooks, recovered in the 1950s, contained detailed sketches of a mechanical knight, and almost certainly represent an extension of the landmark anatomical research described in Vitruvian Man. However, the Industrial Revolution of the late 18th century was the instrumental phase in robotic advancement as it led to the development of key factors, namely complex mechanics and electricity, and the future application of robotics to the field of surgery.

An important early concept in robotic surgery was 'telepresence', a term describing the sensation that you are in one location while being in another. Telepresence robotic arms, a direct descendant of what we recognise as a surgical robot today, were developed in the 1950s. These early master/slave manipulators where initially used in hazardous environments, e.g. the

FIG. 1. The timeline of the history of robots.



bottom of the ocean, in space or moving hazardous material. Further key advances in robotics occurred in the 1980s with the development of microelectronics, computing and the invention of a charge-coupled device needed for digital imaging, video electronics and display technology. The vision of a remote surgery program targeted towards battle field triage, funded by the USA agency DARPA (Defense Advanced Research Projects Agency), was the stepping stone to the development of robots suitable for modern surgical practice.

HISTORY OF ROBOTS IN SURGERY

Robotic devices have taken various forms with specific aims in mind and have been used in several surgical specialities, including orthopaedics, neurosurgery, urology, cardiothoracics, general surgery and gynaecology. The world's first surgical robot was the 'Arthrobot', designed to assist in orthopaedic procedures, and used for the first time in Vancouver, Canada in 1983. In 1985, PUMA 560 (Unimate), the first true non-laparoscopic robotic device, was used to guide precise percutaneous needle placement during brain biopsy. This was followed in 1988 by ROBODOC (Integrated Surgical Systems), a system used in total hip arthroplasty to allow precise pre-operative planning [1]. The first application in Urology occurred in 1988 at Imperial College (London, UK) with the use of the PROBOT in clinical trials to perform transurethral surgery [2]. In 1993, Computer Motion, Inc. (Santa Barbara, California, USA), founded in 1989 and the original leading supplier of medical robots, released AESOP® (Automated Endocope System for Optimal Positioning), a robotic arm to assist in laparoscopic camera holding and positioning. The initial model (1000) was foot pedal controlled but further models were released with voice control (AESOP®2000; 1996) and greater degrees of freedom (AESOP ®3000; 1998) [3]. The CyberKnife® (Accuray), introduced in 1994 for neurosurgical applications, was used to perform stereotactic radiosurgery [4]. In 1998, the ZEUS® Robotic Surgical System (Computer Motion, Inc.) was used for the first full endoscopic robotic procedure (fallopian tube re-anastomosis, Cleveland, USA) and consists of a surgical control centre and three table-mounted robotic arms [5]. In the same year, the first da Vinci® robotic surgery (Intuitive Surgical, Inc., Sunnyvale, CA, USA) was performed, a robot-assisted heart bypass, in Leipzig, Germany [6]. In 2000, the da Vinci® robot was awarded Food Drug and Administration approval in the USA for use in laparoscopic procedures, the same year the first reported robot-assisted radical prostatectomy (RARP) took place in Paris, France [7]. Remote surgery, with the patient and surgeon in different locations, was first achieved in 2001 using the ZEUS® system. A female in patient in Strasbourg, France, had a robotic cholecystectomy performed by a surgeon in New York, USA [8]. Intuitive Surgical, Inc. bought Computer Motion, Inc. in 2003 for $150 million after a fierce legal battle and is now the sole company marketing robotic surgical devices in Urology. Currently, robot-assisted surgery is da Vinci surgery, as all contemporary robotic procedures and publications relate solely to the da Vinci robot manufactured by Intuitive Surgical, Inc.

THE DA VINCIROBOT

Intuitive Surgical, Inc.was founded in 1995 and the first (standard) da VinciRobotic Surgical System was introduced to the market in 1999. The da Vinci robot technology including three-dimensional vision, EndoWrist® instrumentation, Intuitive® motion, ergonomic superiority and surgical precision, and has surmounted the difficulties preventing the widespread adoption of laparoscopic RP (LRP). The first upgrade occurred in 2003, with the addition of a fourth robotic arm, allowing the console surgeon greater control of retraction. In 2006, the da Vinci® S system was released, offering high definition vision and TilePro®, a multi-image display feature. The latest model, da Vinci® Si (2009), has dual console capability, allowing for collaborative surgical opportunities. Intuitive Surgical, Inc. are one of most successful companies of recent times, with an approximate revenue of $1 billion in 2009, up 20% from 2008. Worldwide to-date, 1661 da Vinci systems have been installed (1228 USA; 292 Europe; 141 rest of world, e.g. Australasia) and the total number of robot-assisted procedures performed worldwide between 2007 and 2009 tripled from 80 000 to 205 000 [9]. Over this period the number of da Vinci systems installed in the USA grew by ≈75% and with an estimated 35% growth in the number of procedures in 2010 compared with 2009, the company are targeting a potential 1.8 million procedures annually across all surgical specialities (Intuitive Surgical, Inc. data, Sunnyvale, CA, USA).

HISTORY OF ROBOTS IN UROLOGY

Minimallyinvasive surgery, laparoscopic or robotic, is relevant to a significant number of urological procedures but it is best versed in surgery of the prostate, kidney and bladder. Both approaches possess the well-established advantages of minimallyinvasive surgery namely, less bleeding, decreased transfusion rates, reduced hospital stay, earlier return to activities of daily living, decreased analgesic requirements, and better cosmesis [9,10]. Below we detail the progress that has been made in the surgical approaches relative to RP, partial nephrectomy (PN), pyeloplasty and radical cystectomy (RC).

PROSTATE

From the first descriptions of open perineal prostatectomy in 1905 by Hugh Hampton Young [11]and retropubic RP in 1945 by Terence Millin [12], there have been surgical refinements, advances, improved anatomical knowledge and new techniques in the surgical treatment of prostate cancer. Not ignoring the controversy of whether we need to surgically treat prostate cancer, if surgery is deemed necessary, there is no consensus opinion as to which surgical approach is best but it can be said that time leads to expertise irrespective of approach. In the same way retropubic RP has developed from Millin (1945) [12] to Walsh (1983) [13], LRP has developed from Schuessler (1992) [14] to Guillonneau (2000) [15] and RARP from Abbou (2000) [7] to Vattikuti Institute (2007) [16]. Several recent editorials have soundly concluded that it is the expertise of the surgeon that dictates the outcome and not the surgical approach chosen [17]. The published literature abounds with reports of the virtues of RARP over LRP and retropubic RP but the quality of evidence is best described as 'low' [18]. It is safe to assume both RARP and LRP decrease the estimated blood loss and transfusion rates but arguably this is more a beneficial consequence of the pneumoperitoneum rather than an improved surgical ability to achieve haemostasis afforded by minimallyinvasive surgery. When concerning the 'trifecta' of outcome after RP (cure, continence and potency), there is no evidence that RARP is better than retropubic RP but there is a suggestion that RARP may be superior to LRP [17,19]. A systematic review by Kang *et al.* [20]of 75 original RARP publications concluded that the published literature was limited to observational studies of low methodological quality, which led them to draw into question to what extent valid conclusions about the relative superiority of RARP to other surgical approaches can be drawn.

Naturally, as there are proponents of RARP, there exists a body of opinion that is unconvinced and this scepticism is based upon several factors: lack of evidence of superiority, issues of exorbitant cost, the influence of aggressive marketing and provocative studies in high-profile journals highlighting potential issues with RARP, namely increased 'regret' after RARP [21] and an increased complication rate [22].

Despite all this, the facts speak for themselves. In the USA in 2007, 79 875 RARPs were performed, accounting for 60–70% of all RPs [23]. Medicare beneficiaries (aged >65 years) who received a diagnosis of prostate cancer in 2005 were 14% more likely to have undergone surgery by 2007 than their counterparts whose prostate cancer was diagnosed 3 years earlier [24] and if all radical extirpative surgery for prostate cancer was undertaken robotically it would incur $1.1–2.5 billion additional healthcare costs per year [25]. The proven benefits of minimally invasive surgery coupled with the difficulties in establishing LRP as the 'gold standard' surgical treatment for localised prostate cancer is the background upon which this extraordinary expansion in RARP has occurred. Skilful yet aggressive marketing by Intuitive Surgical, Inc. has a large role in this scenario but the high costs associated with RARP need to be considered. With costs of $1.4–2.2 million per robot, a yearly maintenance fee of $100 000–200 000 and $1000–2000 per patient in disposable robotic instruments, it is not unsurprising a lot of publicly funded institutions have reservations. It is reported you need to perform something in the order of >10 procedures a week or 250 cases a year to achieve cost equivalence with open RP [26].

It is worth remembering that the da VinciSurgical System was not designed solely with RP in mind but once the technology became available and a niche in the market identified, RP was targeted as the index case suited to robotic surgery. For a disease that we often may not have to treat (but do), for an operation that does not necessarily improve outcomes and for the significantly increased healthcare expenditure that using a robot induces, one might muse that the da Vinci robot would not have been as well embraced if stricter technology regulatory bodies existed (akin to the pharmaceutical industry).

KIDNEY

PN

Open PN (OPN) dates back to 1950 and Vincent Vermooten eloquently surmised 'there are certain circumstances when, for a patient's well-being, it is unwise to do a nephrectomy, even in the presence of a malignant growth involving the kidney. It may also occur when the total renal function is such that nephrectomy for carcinoma would result in fatal uraemia. If there is no evidence of metastasis and the neoplasm involves only the cortex of the kidney, excision of the tumour is unquestionably advisable. The question is, whether such a procedure (partial nephrectomy) is ever justifiable when the opposite kidney is normal. I am inclined to think that in certain circumstances it may be' [27]. Open PN is the current standard nephron-sparing surgery (NSS) technique for small renal masses but this is now open for debate with the gain of expertise in minimallyinvasive NSS. Laparoscopic PN was described in 1993 [28], but again its widespread adoption has been limited by all the confounding factors of laparoscopy. In particular, the difficulty of laparoscopic suturing to achieve haemostasis, collecting system closure and re-approximation of parenchyma leads to longer warm-ischaemia times and increased bleeding rates [29].

RAPN was reported in 2004 [30] and there is comparative evidence that RAPN, whilst maintaining the oncological outcomes of open NSS, is superior to laparoscopic PN in terms of length of stay, bleeding and ischaemia times [29]. The improvements in ischaemia and bleeding are a combination of robotic capabilities, sliding clip renorrhaphy and selective clamping techniques, including early clamp removal or a no-clamp 'zero-ischaemia' approach [31]. Naturally, the realisation of the benefits of a robotic approach to PN has led to an increase in the threshold of surgical cases appropriate for NSS. RAPN allows you to safely and effectively remove larger tumours, hilar tumours and more complex masses. It is has even been suggested by some that RAPN is now the new 'gold standard' NSS technique, replacing open PN [32]. It is has been proven that the skills developed during a RARP training programme are eminently transferable to RAPN and surgeons can achieve, with a short learning curve, warm-ischaemia time of <20 min and console time of <100 min [33].

Pyeloplasty

The classic open dismembered pyeloplasty technique was described in 1949 by Anderson and Hynes [34] and remains the benchmark method of treating PUJ obstruction, with a success rate >95%. It is this technique that all other minimallyinvasive surgical approaches to pyeloplasty must emulate. In 1993, Schuessler *et al.* [35] reported the first laparoscopic pyeloplasty and in experienced hands the results of laparoscopic pyeloplasty are equivalent to open dismembered pyeloplasty [36]. However, the difficulties of dissection and suturing are issues encountered by non-expert laparoscopic surgeons and may ultimately affect the long-term outcome. As a reconstructive procedure, the success of pyeloplasty is dependent upon accurate suture placement, a criteria well suited to the suturing dexterity offered by robotic surgery. The feasibility of robot-assisted pyeloplasty (RAP) was first described in a porcine model in 1999 [37] and subsequently in humans [38], and can be effectively performed both trans- and retroperitoneally. In a systematic review and meta-analysis comparing laparoscopic pyeloplasty with RAP, Braga *et al.* [39]have shown that RAP shortens the operative time and hospital stay whilst maintaining a low rate of complications and equivalent outcome. However, the data quality is poor and there is no randomized controlled trial evidence on which to base a definitive recommendation or conclusion for operative approach to pyeloplasty at this time. However, it is foreseeable that with greater adoption of RAP and longer follow-up, the improved anastomotic ability afforded by RAP will translate into excellent long-term outcomes, shorter hospital stay and potentially reduced duration of internal stenting.

BLADDER

The earliest records of open RC to treat bladder cancer date from the late 1800s but the key principles of open RC (ORC) we still adopt today were published by Marshall and Whitmore in 1949 [40]. After authors had demonstrated and established LRP as a treatment strategy for localised prostate cancer, it was rationale that laparoscopic RC (LRC) would be used to treat invasive bladder cancer. The initial report of LRC by Sanchez de Badajoz *et al.* [41] in 1995 has been followed with numerous accounts reporting the ability to laparoscopically perform RC, extended pelvic lymph node dissection and various forms of urinary diversion, either intra- or extracorporeally [42,43]. However, ORC remains the standard of care for invasive bladder cancer. LRC is a time-consuming, challenging procedure even in experienced hands and critics question the standard of lymphadenectomy, the incision for specimen extraction and/or urinary diversion needed and the duration of pneumoperitoneum in an often aged, co-morbid population [44].The technique of robot-assisted RC (RARC) was published in 2003 by Menon *et al.* [45], and it is safe and feasible to perform any manner of urinary diversion robotically [46]. When considering both the many variables concerned with performing a high standard RC and the existing potential to improve morbidity and cancer outcomes after RC, it is not unsurprising that there are numerous recent publications exploring the roll of RARC. There is growing evidence detailing the positive influence of RARC on many of these variables including perioperative morbidity (decreased blood loss, transfusion rate, length of stay), lymph node yield, positive margin status, complication rate, local recurrence rate, operative time and cost [47]. The International Robotic Cystectomy Consortium has published recent reports for the learning curve of RARC. They state an acceptable level of proficiency is possible by the 30th case when trying to achieve proxy measures of RARC quality [48]. They have also shown previous RARP case volume is related to decreased operative time, blood loss and lymph node yield at RARC [49]. Therefore, while ORC remains the accepted standard of care currently, the continued expansion of the evidence base and experience with pelvic robotic surgery will potentially lead to a new 'gold standard' surgical treatment for invasive bladder cancer.

EXPANDING THE ROLE OF ROBOTS IN UROLOGY

Although robotic surgery in Urology has been founded upon RARP, the versatility shown by procedures such as RAPN and

RAP, has led to many surgeons using the robotic platform for a wide variety of urological procedures. As well as malignancy, the robot can now be used to treat benign conditions of the kidney (e.g pyelolithotomy), prostate (e.g. simple prostatectomy), bladder (e.g. diverticulectomy) and testis (e.g. spermatic cord denervation), whilst it also been used in subspecialty areas of female urology (e.g. simple cystectomy, sacrocolpopexy), urolithiasis, reconstruction (e.g. fistula repair, uretero-ureterostomy, ureterolysis), transplant (e.g. live donor nephrectomy) and andrology (e.g. vasectomy reversal, varicocelectomy) [50].

As history shows, there will always be a continuing evolution of surgical techniques and technology, with the ultimate goal of the 'ideal' access, instrument and vision. As multiport laparoscopic radical nephrectomy solidified its position as the 'gold standard' treatment for T1 kidney tumours, authors reported the ability to enhance the 'minimal' aspect with such techniques as laparoendoscopic single-site (LESS) and natural orifice transluminal endoscopic (NOTES) surgery. Equivalent developments are now taking place with robotic surgery. As well as robotic LESS, for which da Vinci have developed specific VeSPA® instruments, and robotic NOTES, there are promising developments in the area of robotic surgery. The most notable is the use of '*invivo* robots'; miniature, dexterous, co-operative robotic devices deployed intracorporeally to perform tasks such as imaging, retraction, tissue manipulation and precision movement [51]. This obviates the need for multiple ports and the docking of a large robot cart, whilst maintaining all the benefits of minimally invasive remote robotic surgery. Undoubtedly, this technological evolution will continue unabated and will be stimulated further by the fact the field of 'laparoscopy' refuses to concede, with themselves developing new articulating instruments to augment single-port surgery further [52].

CONCLUSION

It is truly astonishing that the surgical robot we use today has historical connections with automated inventions described >3000 years ago. The insatiable innovativeness of mankind is responsible for such advancement, and despite reasoned opposition, we perceive the robotic evolution will continue infinitely, securing the place of robots in the history of Urological surgery.

CONFLICT OF INTEREST

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Abbreviations: **AESOP**, Automated Endocope System for Optimal Positioning; **(RA)(L)RP**, (robot-assisted) (laparoscopic) radical prostatectomy; **(RA)PN**, (robot-assisted) partial nephrectomy; **(O)(L)(RA)RC**, (open) (laparoscopic) (robot-assisted) radical cystectomy; **NSS**, nephron-sparing surgery; **RAP**, robot-assisted pyeloplasty; **LESS**, laparoendoscopic single-site surgery; **NOTES**, natural orifice transluminal endoscopic surgery.