INTRODUCTION

The da Vinci Surgical System was introduced in 1999 (Intuitive Surgical Inc., Mountain View, USA), and was approved by the US Food and Drug Administration (FDA) in 2000.¹ The da Vinci robotic-assisted laparoscopic surgery—with the help of enhanced 3D vision, new ranges of movement of laparoscopic tools, and highly responsive robots—ushered in a new era in minimally invasive surgery. So far, four generations of da Vinci have been introduced to the surgical field over the past 20 years.²⁻⁵ The da Vinci’s established intuitive surgical, clinical, technical, and marketing experience is the greatest challenge for all new surgical robot companies. Many hospitals will not be able to accommodate any more robots in their operation theaters, which is a marketing challenge for the new robotics companies. The clinical applications of patented new surgical robotic systems are limited, which needs to be overcome in the coming years.⁶⁻⁸ The annual revenue of the robotic surgery industry has reached around three billion dollars, with an expected annual growth of 15% in the coming years.⁹ Sharing in this growth is strong motivation for new robotic companies. With this new robotic era, we expect to see more robust competition among these robotic companies in the development and marketing of their new robots.¹⁰ The aim of this paper was to comprehensively review the emerging new robotic systems.
METHODS

A thorough non-systematic literature review was performed using the PubMed electronic search engine. The following words were searched: “Da Vinci robot system” (n = 990), “robotic surgical system” (n = 6,303), and “new robotic surgical device” (n = 950). Study selection criteria were review articles, preclinical studies, and first clinical trials of these robotic surgical systems. Additional information was obtained from each robotic system company’s official website and from press release articles. The included figures were sourced from pictures previously published in medical journals. This review focuses on robotic systems that have urological or other potential applications.

ROBOTIC SURGICAL SYSTEMS

The robotic systems are summarized in Table 1.

DA VINCI SURGICAL SYSTEM

The introduction of the da Vinci surgical system revolutionized many surgeries over many surgical specialties. The da Vinci system also created a new surgical history milestone: from open surgery, to laparoscopic and endoscopic surgery, to robot-assisted surgery. The adoption of robotic surgery has grown rapidly over all surgical specialties (Figure 1).11

The long surgical innovation patency period gave intuitive surgery and elevated stature in the robotic surgical system market. Many surgical platforms were developed, as was trust from surgeons, patients, and health authorities. Additionally, there have been extensive clinical publications on top of a strong marketing strategy with well-distributed distributors across the globe. Over the last 20 years, approximately five million surgeries have been performed with da Vinci Robots,12 which has given them a massive cumulative experience and competitive advantage.

The Da Vinci surgical system solved several challenges of standard laparoscopic surgery including improved 3D/HD vision, better dexterity, seven degrees of motion (DOF) by the EndoWrist system, and effective simulation training software. Intuitive surgery brought to surgeons da Vinci S, Si, Xi, X, and the gamechanger of their SP (single port) da Vinci Robotic system (Figure 2).13

NEW ROBOTIC SURGICAL SYSTEMS AND COMPANIES

Senhance (Telelap ALF-X)

The recently (approved October 2017) FDA-approved ALF-X (Senhance; Trans-Enterix®, Morrisville, USA) is a new multiport robotic system. Fanfani et al reported 80 hysterectomy cases from October 2013 to May 2014 with the ALF-X system.14 For urology, a porcine model of robot-assisted partial nephrectomy has been reported.15 It has the advantage of totally independent surgical arms, haptic feedback, and eye tracking systems.16,17 Because of independent surgical arms, this system requires a spacious operative room.

Revo-i®

Revo-i® (Mere company Inc., Yongin, South Korea) is the first Korean robotic system, and received Korean FDA approval for clinical use in August 2017. Revo-i® has a control console, a four-arm robotic cart, a vision cart with HD quality, and multi-use endoscopic instruments (Figure 3).13,18,19 It has a design similar to that of the da Vinci Si robot. Abdel Raheem et al reported their porcine model preclinical study in 2016,8 and a clinical trial of robotic cholecystectomy in 2017.20

Micro Hand S

The Micro Hand S first Chinese robotic system was developed by Tianjin University in collaboration with Central South University in 2013.21 It is similar to the da Vinci Si robot (Figure 4).22 In 2014, the first clinical trial was reported by Yi et al, who treated patients with gastric perforations and two patients with acute appendicitis.22

SPORT

The Single Port Orifice Robotic Technology (SPORT) was developed by the Titan Medical Company (Toronto, Canada).23 It has an open console system that supports HD/3D vision with a multi-articulated robotic instrument. SPORT has been used to perform robotic single-port partial nephrectomy using an animal model,10 but has not been used in human clinical studies. The company will have a challenging market, as the SP da Vinci Robot has already launched in multiple countries and was featured in a handful of clinical publications.

Versius

Versius (Cambridge Medical Robotics, Cambridge, UK) was created following the idea of independent robotic arms with separate functional units.24 It has an open console design. The robotic arm consists of three joints which act as the shoulder, elbow, and wrist. These joints provide a more human-like range of arm movements. The creators of Versius also introduced a haptic feedback system. The company adopted a different marketing strategy in the form of a managed-service contract system,25 without an upfront capital payment. This should attract mid-range to small hospitals to add robotic surgeries to their existing services.

MiroSurge

MiroSurge (Medtronic, Minneapolis, USA) is an operative table mounted robot, as the robotic arms are attached to the operation
### TABLE 1  Robotic surgical systems summary

| Robot        | Uses       | Port | Robot Cart | Arm | Console | Controller | Enhanced imaging | Vision | Haptic feedback | Eye tracking | Instrument | Arm DOF | Instrument DOF | Cost (Million $) |
|--------------|------------|------|------------|-----|---------|------------|------------------|--------|----------------|--------------|------------|---------|----------------|------------------|
| DV Xi        | MIS        | MP   | Single     | 4   | Close   | Joystick   | FireFly          | 3D HD  | No             | No           | 10 uses    | 3       | 7                 | 1-1.5            |
| DV SP        | MIS        | NOTES| SP         | 1   | Close   | Joystick   | FireFly          | 3D HD  | No             | No           | 10 uses    | Rotational | Flexible | 2               |
| Senhance     | MIS        | MP   | Multiple   | 4   | Open    | Joystick   | NOVADAQ          | 3D HD  | Yes            | Yes          | Unlimited  | 3       | 7                 | 1.3              |
| Revo-i       | MIS        | MP   | Single     | 4   | Close   | Joystick   | No               | 3D HD  | No             | Yes          | No         | 20 uses  | 3               | 7 NA             |
| Micro Hand S | MIS        | MP   | Single     | 4   | Close   | Joystick   | No               | 3D HD  | No             | No           | NA         | 3       | 7               | NA              |
| SPORT        | MIS        | NOTES| SP         | 1   | Open    | Hand-controller | No      | 3D HD | NA             | NA           | NA         | NA      | Rotational | Flexible | NA               |
| Versius      | MIS        | MP   | Multiple   | 4   | Open    | Joystick   | No               | 3D HD  | NA             | NA           | NA         | 3       | 7 Managed service contract system |
| MiroSurge    | MIS        | MP   | Multiple   | 3   | Open    | Joystick   | No               | 3D HD  | Yes            | NA           | NA         | 3       | 7 NA               |
| Bitrack      | MIS        | MP   | Single     | 3   | Open    | Joystick   | No               | 3D HD  | NA             | NA           | NA         | 3       | 7 NA               |
| Medicaroid   | MIS        | MP   | Single     | 4   | Open    | Joystick   | No               | 3D HD  | NA             | NA           | NA         | 3       | 7 NA               |
| Verb         | MIS        | MP   | Single     | 4   | Open    | Joystick   | NA               | 3D HD  | NA             | NA           | NA         | NA      | NA               |
| SurgiBot     | LESS       | SP   | Single     | 1   | No console | Laparoscopic Handle | NA   | 3D HD | NAP            | NAP          | Rotational | Flexible | NA              |
| PROCEPT      | NOTES      | NAP  | Single     | 1   | No console | NAP             | Real-time US | HD    | NAP            | NAP          | NAP        | NAP     | NAP               |
| EMARO        | MIS        | SP   | Single     | 1   | No console | Pneumatic Gyroscope | NAP | HD    | NAP            | NAP          | Rotational | NAP    | NA               |
| Roboflex     | NOTES      | NAP  | Single     | 1   | Open    | Joystick   | NAP             | HD    | NA             | NAP          | NAP        | NAP     | Rotational | Flexible | NA               |

**Note:** DOF, degree of freedom; DV, da Vinci; LESS, laparoendoscopic single port surgery; MP, multi-port; NA, no available data; NAP, not applicable; NOTES, natural orifice transluminal endoscopic surgery; SP, single port.
table. The developers used the concept of an open console with an autofocus feature. MiroSurge is a micromotor driven instrument with a wide range of motion that also provides tactile feedback. We are still waiting for their clinical trials and applications to further assess this system’s potential. The company was planning to launch clinical studies in India, but does not appear to have done so yet.26–28

5.7 | Bittrack

A prototype of the Bitrack System (Rob Surgical Systems S.L., Barcelona, Spain)29 was introduced in 2015. This was followed by a clinical validation phase to obtain European market approval. As with all new robotic systems, no sufficient clinical data exist to affirm the feasibility or superiority of this system to currently available robots. Other details of the system have been secured from public access.

5.8 | Medicaroid

Medicaroid (Kobe, Japan) was introduced in 2016. It was developed by a company in Silicon Valley consisting of a collaborative group of Sysmex and Kawasaki.30,31 Medicaroid is another table-mounted robot that consists of three arms and an operating console.10 We are still waiting for their clinical trials to begin.
Verb Surgical, established in 2015, is the result of the collaboration between Google and Johnson & Johnson. They have introduced artificial intelligence (AI) to robotic systems with additional feedback systems to operating surgeons. The company's long-term plan is to move toward a new era of robotic-guided (rather than robot-assisted) surgery. Over the long-term, the company seeks to develop robotic surgery technology, fully performed by robots. To this end, no detailed information is available publicly about either the robot system or design. However, such information is anticipated in the near future, considering the collaboration of high-tech and well-established innovative surgical companies.
5.10 | SurgiBot

The SPIDER Surgical System developed and improved by the TransEnterix Company, was later sold to Great Belief International Limited in China. SurgiBot is a bedside base robot that offers adjustable triangulation and multi-quadrant movability with 3D-enhanced HD vision. A preclinical trial involving urological procedures was reported in 2015.

5.11 | PROCEPT

Aquablation (Aquatic ablation therapy) is one of the first endoscopic robots to perform surgery on its own, with the help of live ultrasound guidance. It was developed by the PROCEPT Company and rendered treatment of benign prostatic hypertrophy (BPH) a day-case procedure, possible even in outpatient setups, with proven efficiency in short- and long-term follow-up. Its mechanism of action depends on the aqua beam system software with a surgeon’s pre-defined contour, assisted by ultrasound-calculated length, depth, and width of the planned resection. The WATER study showed that Aquablation therapy results were as effective as the gold standard transurethral resection of the prostate (TURP).

5.12 | EMARO

EMARO is the first pneumatically powered endoscopic manipulator robot with an air-pressure system (Figure 5). It was developed by a Japanese company based in Tokyo. The operator drives the robot with the help of a head sensor. We await more information on its clinical application and studies.

5.13 | Avicenna Roboflex

Avicenna Roboflex (Elmed, Ankara, Turkey) was introduced for intra-renal surgery using a robotically driven flexible ureterorenoscope. It is an open console system with enhanced HD vision. The Avicenna Roboflex offers full control of flexible ureteroscopy, irrigation, LASER fiber, and fluoroscopy. The initially published clinical data are promising.

6 | DISCUSSION

Robotic-assisted surgery established a new era and novel milestones in the history of surgery and its adoption among surgeons was extremely fast. It has reshaped the oncological and reconstructive surgeries throughout all surgical specialties. In part, these recent surgical advancements are the result of what the robot offers the surgeon: a tool set unlike any tools that proceeded it. Urologists exhibited precedent adoption of robotic surgery, especially for prostatectomy and partial nephrectomy. Even endourology had demonstrated growing use of robotic endourological surgeries. The intuitive surgery monopolized the surgical robot market over more than a decade, which gave the first systems a considerable competitive advantage. This advantage was the result of a strong market, trust of the surgical community, accumulative technical experience, and—last but not least—the numerous high-quality clinical studies which have supported robotic systems and surgeries. As the patent rights expire, the robotic
surgery market will be increasingly competitive, thus raising the bar for robotic companies.

Although the da Vinci system propelled many robots to market, there has been no significant improvement in the console. The closed console system compromised the surgeon’s awareness of his/her surroundings in the operative theater. In contrast, the ALFX system offers an open console system, which is a move in the right direction. Haptic feedback is a particularly important feature that is lacking in the current da Vinci system, while the Telelap ALF-X took the initiative step of providing haptic feedback with their robots. Given the emerging surgical trends of single-site and natural orifice surgeries, we expect that robotic surgery will revolutionize these types of surgeries through the development of advanced surgical robots and minimally invasive technologies. Many companies are currently developing their own surgical robots; however, many of these projects are confidential at this moment. This list of available surgical robots is non-exhaustive, with each day bringing newly developed technology.

7 | CHALLENGES TO NEW ROBOTIC SYSTEMS

New robotic companies face many challenges. The open surgical robot market is competitive, and cost is a significant factor in the success or failure of any one system. Companies whose robots are priced similar to existing trusted and tested robots may fail to sell their product. Unfortunately, the development of new, high-quality technology is costly. Future studies on robot pricing are needed.

Another challenge is where to sell the robots. Currently, most high-volume robotic surgery centers have reached their operative room capacity for accommodating robots. When new robotic companies target mid-to-small range hospitals, they do so at the risk of potentially disappointing initial clinical results, which may further reduce their market value.

Additionally, how will health insurance providers consider new surgical robots? Will these novel systems be covered by insurance? Will insurance companies classify all robotic surgery systems as “robotic,” regardless of the robot used, or will their classification schemes vary relative to the robot that is used? Many health insurance providers still do not cover robotic surgery by the da Vinci system, even given their long history in the field. Also, how will surgical robots affect medical litigation within the courts? Which robots be considered superior to other robots or to surgeons themselves? What if new robots demonstrate technical errors? These questions remain unanswered.

9 | CONCLUSION

This new era of robotic-assisted surgery attracts both surgeons and patients. Robotic surgery has reshaped our surgeries over the last two decades, and robots are now used in almost every surgical field. Still, as surgeons, we continue to look—with great interest—to new robotic companies that may be able to provide better robots in a more cost-effective manner. Future studies that compare individual robotic systems are needed to further evaluate the strengths and weaknesses of each system, with an eye on the continued improvement of robotic surgery technology.

CONFLICT OF INTEREST
None.

AUTHOR CONTRIBUTIONS
Rha, Koon Ho: Protocol/project development/Data analysis/Manuscript writing/editing.
Almujalhem, Ahmad: Data collection or management/Data analysis/Manuscript writing/editing.

ORCID
Ahmad Almujalhem https://orcid.org/0000-0003-0401-6758
Koon Ho Rha https://orcid.org/0000-0001-8588-7584

REFERENCES
1. Intuitive Surgical Company. Da Vinci Robot Patency 2019. Available from: https://www.intuitive.com/en-us/about-us/company/legal/patent-notice
2. Rao R, Nayyar R, Panda S, Hemal AK. Surgical techniques: robotic bladder diverticulectomy with the da Vinci-S surgical system. J Robot Surg. 2007;1(3):217–20.

3. Kang S-W, Lee SC, Lee SH, Lee KY, Jeong JJ, Lee YS, et al. Robotic thyroid surgery using a gasless, transaxillary approach and the da Vinci S system: the operative outcomes of 338 consecutive patients. Surgery. 2009;146(6):1048–55.

4. Tobis S, Knopf J, Silvers C, Yao J, Rashid H, Wu G, et al. Near infrared fluorescence imaging with robotic assisted laparoscopic partial nephrectomy: initial clinical experience for renal cortical tumors. J Urol. 2011;186(1):47–52.

5. Kaouk JH, Haber G-P, Autorino R, Crouzet S, Ouzzane A, Flanamd V, et al. A novel robotic system for single-port urologic surgery: first clinical investigation. Eur Urol. 2014;66(6):1033–43.

6. Gidaro S, Altobelli E, Falavolti C, Bove AM, Ruiz EM, Stark M, et al. Vesicourethral anastomosis using a novel telesurgical system with haptic sensation, the Telelap AlF-X: a pilot study. Surg Technol Int. 2014;24:35–40.

7. Kim DK, Park DW, Rha KH. Robot-assisted partial nephrectomy with the REVO-I robot platform in porcine models. Eur Urol. 2016;69(3):541.

8. Abdel Raheem A, Troya IS, Kim DK, Kim SH, Won PD, Joon PS, et al. Robot-assisted Falloplian tube transection and anastomosis using the new REVO-I robotic surgical system: feasibility in a chronic porcine model. BJU Int. 2016;118(4):604–9.

9. Perez RE, Schwartzberg SD. Robotic surgery: finding value in 2019 and beyond. Ann Laparosc Endosc Surg. 2019;4:51.

10. Rassweiler JJ, Autorino R, Klein J, Mottrie A, Goezen AS, et al. Future of robotic surgery in urology. BJU Int. 2017;120(6):822–41.

11. Intuitve Surgical, Inc. Annual Report 2019. Available from: https://www.intuitive.com/media/investor_relations/annual_report/2019_AR.pdf.

12. Khandalavala K, Shimon T, Flores L, Armijo PR, Oleynikov D. Emerging surgical robotic technology: a progression toward microbots. Ann Laparosc Endosc Surg. 2019;5:1–18.

13. Gosirisrikul C, Don Chang K, Raheem AA, Rha KH. New era of robotic surgical systems. Asian J Endosc Surg. 2018;11(4):291–9.

14. Fanfani F, Restaino S, Alletti SG, Fagotti A, Monterossi G, Rossitto T, et al. TELELAP ALF-X robotic-assisted laparoscopic hysterectomy: feasibility and perioperative outcomes. J Minim Invasive Gynecol. 2015;22(6):1011–17.

15. Bozzini G, Gidaro S, Taverna G. Robot-assisted laparoscopic partial nephrectomy with the ALF-X robot on pig models. Eur Urol. 2016;69(2):376–7.

16. Gidaro S, Buscarini M, Ruiz E, Stark M, Labruzzo A. Telelap AlF-X: a novel telesurgical system for the 21st century. Surgical Technol Int. 2016;69(2):376–7.

17. Senhance Surgical. Senhance Robot 2020. Available from: https://www.senhance.com/.

18. The World’s First Pneumatic Endoscope Manipulator Holds Promise for Quality Surgery [Internet]. 2015. [cited 2015 Aug 4]. Available from: https://www.titech.ac.jp/eng_news/2015/031929.html.

19. Riverfield Inc. EMARO Robot 2020. Available from: https://www.riverfieldinc.com/en/product/.

20. MedTRONIC Surgical. Versius Robot 2020. Available from: https://www.medtronic.com/versius/.

21. Micro Hand S Robot [Internet]. Available from: http://www.tju.edu.cn/english/info/1011/4091.htm.

22. Yi B, Wang G, Li J, Jiang J, Son Z, Su H, et al. The first clinical use of domestically produced Chinese minimally invasive surgical robot system “Micro Hand S”. Surg Endosc. 2016;30(6):2649–55.

23. Titan Medical. Titan Robot 2020. Available from: https://www.titanmedical.com/