DISCUSSION PAPER

ROBOTICALLY-ASSISTED SURGICAL DEVICES

INTRODUCTION

The FDA has created this discussion paper to outline topics related to the design, development, evaluation and regulation of robotically-assisted surgical devices (RASD), which will be discussed in our public workshop on the topic. These minimally invasive devices enable a surgeon to use computer, robotic and software technology to control and move surgical instruments through one or more small incisions in the patient's body for a variety of surgical procedures. The benefits of RASD may include the devices' ability to facilitate minimally invasive surgery and assist with complex tasks in confined areas of the body.

The FDA recognizes that moving RASD from the laboratory to the clinical environment can be challenging and may be facilitated through advancement of scientific and clinical knowledge, and by addressing questions concerning training, case-selection, reliability and safety, and uncertainty in the regulatory and marketing pathways. This document covers these topics, which will be discussed at the FDA Public Workshop being held at the White Oak Campus in Silver Spring, MD on July 27 & 28, 2015.

Throughout this discussion, the FDA will focus on supporting the mission and vision of the Center for Devices and Radiological Health (CDRH) by discussing issues related to protecting and promoting public health while striving to bring timely, high-quality, safe and effective medical devices to U.S. patients.

This discussion paper is organized to provide an overview of the state-of-the-art in RASD:

1. Technological Overview
2. Regulatory Review
3. Clinical Review
4. Training Review
5. Post-Market Surveillance
6. Conclusion
7. References
8. Appendix 1

The goal of this public workshop is to obtain public feedback on scientific, clinical, and regulatory challenges and opportunities associated with RASD in order to develop an appropriately balanced, scientifically sound framework for the evidentiary requirements for RASD seeking:

- Market entry or iterative changes to a marketed RASD,
- Interoperability – among RASD and with non-RASD,

- Generalized claims,
- Specific procedural claims – including pioneering procedures that are newly enabled by RASD,
- Use of training and simulation as a risk mitigation measure, and
- Use of literature and registry data to justify claims.

The above challenges and follow-up questions are detailed in Appendix 1 for discussion during the workshop.

FDA is committed to enabling RASD technology in a responsible, efficient, well-informed manner for maximal patient benefit. It is important to note that the information contained in this document is not meant to be a comprehensive review of RASD nor does it establish policy or convey the FDA's practices or formal views; rather, the content is provided as background information to facilitate discussions at the Public Workshop.

1. TECHNOLOGICAL REVIEW

DEFINITION AND BACKGROUND

What are RASD?

RASD enable the surgeon to use computer, software, and robotic technology to control and move surgical instruments through one or more small incisions in the patient's body to perform surgeries. The benefits of RASD may include the device's ability to facilitate minimally invasive surgery and assist with complex tasks in confined areas of the body. RASD are not considered to be surgical robots, since the definition of a robot is an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks".[1] Therefore, by definition, there are no *surgical robots* on the market that perform minimally invasive surgical tasks autonomously. Instead, we call the currently marketed products *robotically-assisted devices,* which perform tasks guided by the surgeon's control.

Currently marketed RASD generally have the following three components:

- A console, where the surgeon controls the system. The console is the control center of the system and allows the surgeon to view the surgical field and control movement of the surgical instruments and the camera (endoscope) though a 3D monitor;
- A bedside cart that includes multiple hinged mechanical arms, camera (endoscope) and surgical instruments that a surgeon controls during the surgical procedures; and
- A separate cart that contains supporting hardware and software components, such as an electrical surgical unit (ESU), suction/irrigation pumps, and light source for the endoscope.

Most surgeons use multiple surgical instruments and devices with the RASD, such as scalpels, forceps, graspers, dissectors, cautery, scissors, retractors and suction irrigators. RASD technology can and does allow access to narrow, confined and tight operative sites, enhancing microsurgery. It can also scale motion, reduce or eliminate tremor, and enhance the visual field. Telesurgery is also being developed so that the surgeon can operate on patients in remote locations across the globe or even for space aeronautics use, presuming a reliable network connection. Ultimately, fully autonomous robotic surgical technology may be developed for untold uses. [2;3] Additional information on robotic (computer)-assisted surgical systems can be found at the FDA's *Computer-Assisted Surgical Systems* website.[4]

SYSTEM PERSPECTIVE

It is important to recognize the RASD are not used in the operating room in isolation. Rather, the RASD is part of a larger sociotechnical system that includes people (e.g. patients and healthcare providers), health care organizations, other medical products, medical device developers and manufacturers, processes (actions and procedures performed during the delivery of health care), and the environment of use.

Optimal patient care using RASD requires each aspect of the system to be operating with proficiency. For example, a patient may have a bad outcome even if their surgeon is highly trained and skilled if the RASD does not function well. Similarly, the RASD may perform as intended and as designed, but if operating room personnel do not follow appropriate processes and procedures to assure safe care of the patient during the procedure, the patient may not have an optimal outcome.

Because of the complexity of the health care delivery system in which the RASD is used, certain key factors should be considered.

First, an understanding of the fundamental technological characteristics of RASD is necessary so that changes to a device that could affect the performance of the RASD system can be easily detected. These relationships may not be obvious due to the complexity of the system. For example, a small time delay between the robotic instrument tip (or end effector) and the operating surgeon's action at the surgeon console can affect the ability of the surgeon to complete each surgical task.

Second, an understanding of the interdependence and interoperatibility of each component of the RASD system is necessary. Safe designs of RASD include feedback mechanisms either built into the device design or provided to alert system operators. For critical components, redundancy and fail safe designs should be considered to ensure reliability of the system.

Third, RASD training for the user and the operating room (OR) team are important considerations. Surgical simulators that have been developed and are continuing to evolve and improve can play an important role. As with the aviation industry, training for situations that

stress the user and the system could serve as a means for designing corrective actions to prevent bad experiences from being duplicated by other ORs.

Finally, patient selection for RASD procedures cannot be overlooked. Due to technical limitations of the current RASD technology, proper patient selection can maximize the success of the procedure and minimize the risk to the patient.

It is important to bear in mind this systems perspective and how all stakeholders have a responsibility for helping realize its full potential.

HISTORY OF RASD IN THE U.S.

Year	Event
1993	The first device to bring robotic technology to abdominal surgical procedures was the Automated Endoscopic System for Optimal Positioning - AESOP (K931783), manufactured by Computer Motion. The AESOP consisted of an operating room table-mounted robotic arm that held a laparoscopic camera controlled via either voice command or foot pedal.
1997	The Monarch Laparoscopic Scope Manipulator and Control System (K965001) manufactured by Intuitive Surgical added two additional robotic arms holding disposable wristed instruments, called "end effectors." A distinct feature of the Monarch system was the tele-operator (surgeon) console, which consisted of a monitor displaying images obtained by a laparoscopic camera inside the patient's body and a "Master" manipulator. Through the Master manipulator, the surgeon could control the movement of three robotic "Slave" manipulators that held the laparoscopic camera and the surgical instruments.
2000/2002	The *da Vinci* Surgical System (K990144) from Intuitive Surgical and the ZEUS robotic Surgical System (K021152) from Computer Motion were the next evolutionary step in the development of RASD. These systems were initially cleared for laparoscopic surgical procedures such as cholecystectomy and Nissen fundoplication. Additional indications for urology, gynecology, and cardio-thoracic procedures were added in subsequent 510(k) submissions.
2003	Intuitive Surgical merged with Computer Motion leading to discontinuation of the ZEUS system.
2009	Transoral robotic surgery (TORS) was introduced via the *da Vinci* Surgical System.
2011	Intuitive Surgical introduced a new set of instrumentation that allows surgeons to perform single incision laparoscopic cholecystectomy procedures on the IS3000 (K112208).
2014	Intuitive Surgical introduced a new *da Vinci* Surgical System, the SP999 (K131962). Unlike previous models, the SP999 was a true single-port RASD and has been indicated for use in urological surgical procedures.
Today	There are reports of new RASD manufacturers seeking to gain market entry. There are also academic institutions that are actively conducting research in haptics,

computer vision, augmented reality, compensation for motion of surgical targets, cooperative telesurgery over the internet, human/machine interfaces, and autonomous sub-tasks.

TECHNICAL ADVANTAGES AND CHALLENGES

When compared to conventional laparoscopic techniques, RASD introduce several potential technical benefits and risk factors. Briefly, benefits may include improved positioning, control, and visualization. Some of these potential advantages and challenges are described below. Discussion on these and other technical factors is encouraged.

There are several potential benefits to position and control with RASD technology. On the control side, the surgeon's hand movements can be scaled down to control the instruments in smaller, more precise motions. Hand tremors may be dampened or filtered out as well.[5] Improvements to instrument control may enable surgeons to perform complex tasks such as suturing and knot tying in confined spaces.[6] On the instrument side, there is potential for navigating the instruments/endoscope to anatomic sites that cannot be accessed via straight/fixed laparoscopic instruments.[7]

Some users have also credited computer-assisted surgical systems with improved high resolution 3D visualization, based on technology developed for currently marketed RASD platforms. While it is important to consider the impact that enhanced depth perception brings to RASD procedures, it should be noted that this feature is an improvement to endoscopic technology, thus, by definition it is not strictly a unique RASD advancement. Some surgeons who use RASD technology find it to be a more natural movement versus standard laparoscopic procedures, finding that RASD technology has more of an open procedure feel.[8] There is some evidence that the learning curve is shorter with RASD as compared to standard laparoscopy.[2;3]

HAPTICS

The most commonly cited disadvantage of RASD technology is the lack of sensory touch feedback; the surgeon is not able to palpate and sense the feel of soft tissues.[9;10] Research to develop haptic tools, e.g. force feedback, has been ongoing for several years. In order to mitigate the lack of haptic feedback and provide the surgeon with better visual information in lieu of touch, improvements to 3D visualization have been made. However, there is some controversy over what constitutes haptics and whether or not they are necessary in RASD.

HUMAN FACTORS

Human factors pose unique challenges due to the increased complexity of controls. Features not previously available on traditional laparoscopic systems may require additional manual control hardware such as foot pedals and joysticks, or operating routines such as signaling hand motions or 'double-clicking' buttons. Failure to consider limitations in human capabilities when designing multiple controls can lead to issues with safety and effectiveness, as has been the experience with aviation automation. [11;12]

DESIGN

There are technical considerations related to the internal design as well. Factors associated with robotic linkages, computer control, and complex electro-mechanical components, among others, add benefit and risk factors. For example, safe design of a robotic system has considerations for collision avoidance with obstacles and with itself, collision recovery procedures if obstacles are encountered, and appropriate cautions for staff to minimize the risk of collisions. Latency, defined as lag time between user command and instrument function, may be a factor to consider, especially in systems that are controlled from a remote location (tele-robotics). Standard concerns for complex medical device systems, such as software reliability, reprocessing instruments with complex geometries, cybersecurity for networked systems, etc. would also apply to RASD. Furthermore, the internal workings may offer benefits over manual laparoscopic tools by recording and reporting device status and function for medical studies, maintenance scheduling, and post-market surveillance.

DEVICES, ACCESSORIES & COMPONENTS LABELED FOR USE WITH RASD

A number of medical devices may interact with a RASD, including RASD accessories[*] and stand-alone devices. These devices may be fully integrated and/or directly controlled by the RASD system, such as the RASD instrumentation, or they may be devices labeled to work in conjunction with the RASD, such as a laser system. Medical devices labeled and indicated for RASD may introduce novel technical and regulatory challenges. For example, devices that require additional maneuvers or controller interfaces may add tasks and possibly increase complexity associated with RASD system use. Additional compatibility concerns may exist for devices integrated to work with RASD software, controllers, etc. Additional challenges are introduced if a product intended for use with a RASD is designed and/or manufactured by a "third party" company different from the RASD manufacturer.

Medical devices not fully integrated with the RASD can face unique challenges specific to the device design (e.g., a device designed to be held and positioned with a RASD-controlled gripper may need a tab or other connection point to allow stable grasping). Compatibility issues can also include the ability of the RASD to control or manipulate the additional device, potential damage of one of the devices caused by either the RASD or additional device, electromagnetic compatibility (EMC) concerns, etc. These types of compatibility challenges apply to the initial RASD and supplemental technology, as well as future RASD and supporting device iterations.

2. REGULATORY REVIEW

The FDA's CDRH classifies all medical devices based on the risks associated with the device. Devices are classified into one of three categories: Class I, Class II, or Class III. Class I devices

[*] For the purposes of this paper and corresponding workshop, accessory devices for RASD are defined as devices that are intended to support, supplement, and/or augment the performance of the RASD.

are deemed to be low-risk and are therefore subject to the least regulatory controls. Class II devices are moderate risk devices, and Class III devices are life sustaining and/or the highest risk devices and are therefore subject to the highest level of regulatory control. Additional information regarding device classification is available at the FDA's *Classify your Medical Device* website.[13]

Regulatory pathways used for medical devices include the premarket notification [510(k)], Premarket Approval Application (PMA), and the *de novo* classification process.

RASD are currently regulated as Class II 510(k) devices, under the "Endoscope and accessories" regulation (21 CFR 876.1500). Therefore, in order for a new or modified RASD to obtain FDA clearance, the new or modified device must be demonstrated to be "substantially equivalent" to a "predicate" (legally marketed) device. To find a new device substantially equivalent to a predicate device, FDA must find that the two devices have the "same intended use." FDA must then determine that the two devices have "the same technological characteristics," or that any differences in technological characteristics do not raise different questions of safety and effectiveness and that the new device is as safe and effective as the predicate device.[**]

Originally, RASD were found substantially equivalent to laparoscope holding devices, and were therefore placed in the "endoscope and accessories" regulation. These initial clearances were made by considering RASD as surgical tools (i.e., demonstrated ability to grasp, cut, dissect, retract tissues and coagulate bleeding, etc.). Therefore, RASD have been cleared for general surgical indications such as urological surgeries, general laparoscopic surgeries, gynecological laparoscopic surgeries, etc. with the premarket testing demonstrating the capability of performing "representative" tasks or procedures. In this context, such general claims for device use in a specialty have not typically assessed every procedure performed by that specialty.

FDA has published guidance on the general principles that are considered in determining when a specific indication for use is reasonably included within a general indication for use of a medical device for purposes of determining substantial equivalence (see Guidance for Industry on General to Specific Intended Use[14]). Generally, FDA has considered new, specific indications for use for RASD to fall within the scope of the cleared general "intended use" for RASD. Specific indications for use are typically supported by additional data, which may include pre-clinical, animal, literature, or clinical data.

3. CLINICAL REVIEW

COMMON USES

[**] See section 513(i) of the FD&C Act

The most commonly cited, FDA-cleared RASD for endoscopic surgery is the *da Vinci* Surgical System (Intuitive Surgical, Inc. Sunnyvale, CA). Intuitive Surgical currently markets the only RASD cleared for use in the U.S. The indications for use for the most recently cleared *Xi* system (Model IS4000) are as follows:

> The Intuitive Surgical Endoscopic Instrument Control System (*da Vinci* Surgical System, Model IS4000) is intended to assist in the accurate control of Intuitive Surgical Endoscopic Instruments including rigid endoscopes, blunt and sharp endoscopic dissectors, scissors, scalpels, forceps/pick-ups, needle holders, endoscopic retractors, electrocautery and accessories for endoscopic manipulation of tissue, including grasping, cutting, blunt and sharp dissection, approximation, ligation, electrocautery, suturing, and delivery and placement of microwave and cryogenic ablation probes and accessories, during urologic surgical procedures, general laparoscopic surgical procedures, gynecologic laparoscopic surgical procedures, general thoracoscopic surgical procedures and thoracoscopically-assisted cardiotomy procedures. The system can also be employed with adjunctive mediastinotomy to perform coronary anastomosis during cardiac revascularization. The system is indicated for adult and pediatric use. It is intended to be used by trained physicians in an operating room environment in accordance with the representative, specific procedures set forth in the Professional Instructions for Use.

A summary of the information used to clear this device for these indications is available at FDA's 510(k) *Pre-market Notification* website.[15]

Transoral robotic surgery (TORS) procedures are not indicated for the IS4000 systems but are available for earlier models of the *da Vinci* Surgical Systems.

As the above indications for use illustrate, the *da Vinci* Surgical System has broad applications. However, the *da Vinci* Surgical System is most commonly used in urological and gynecological procedures.[2;3;6;11-12;16] Other surgical specialties have been slower to adopt the technology for various reasons, *e.g*. resistance to change or cost justification.[2;3;17] The development of additional safe and effective devices, accessories and components for use with existing and future robotic-assisted systems may significantly expand the clinical use of RASD.

BENEFITS/RISKS

The overall benefits and risks associated with RASD technology depend on a number of factors including but not limited to the technology itself, as well as the disease or condition being treated. Published literature indicates that the technical benefits of RASD technology are definable. However, there are differing views as to whether technical benefits consistently translate to clinical benefits (improved outcomes) for patients over conventional laparoscopic/endoscopic surgery. A summary of the benefits, risks, and outcomes for common indications and example procedures is outlined in Table 1. Many of the example RASD procedures in Table 1 and referenced in the sections below have not been cleared or approved by FDA.[2;3;18-21]

Primary Indications	Procedures Indications	Benefits	Risks	Outcomes	Ref.
General	• Bariatric • Heller Myotomy • Cholecystectomy • Hernia	• +access • - recovery time • - infection rate • - EBL	• ↑ OT&C • CtOC	• NSCB • Possible ↓ in mortality	19;22-31
Cardio-thoracic	• Mitral Valve • Coronary	• - cost (CABG) • - cross-clamp time in complex valvuloplasty • + view and access • - transfusion needs • - post-operative pain • - recovery time	• ↑ OT&C • Stroke (rare) • CtOC	• Slow RAS technology uptake in the community • NSCB • Steep learning curve	19;32-34
Gynecology	• Uterine Fibroids • Endometriosis • Excessive Menstrual Bleeding • Pelvic Prolapse • Gynecologic Cancer	• Complex cases • Microsurgery • - EBL • - post-operative pain • Morbid obesity	• ↓ access options • No haptics • ↑ OT&C • CtOC	• + view and access • + outcomes in malignancies • NSCB	8;20;35-40
Urology	• Bladder • Kidney • Prostate	• - EBL • - recovery time • - short-term complication rates	• ↑ OT&C • No haptics	• NSCB • ↑ view and access • ↑ outcomes in malignancies	19;21;41-45
ENT	• Benign & malignant tumors (T1 & T2) • Benign base of tongue resection	• - morbidity • + swallow function • - tracheostomy rates • - recovery time • +access/visualization • + cosmesis • - pain	• Bulky instrumentation • Bleeding • Nerve injury	• Inconclusive	46;47
Colorectal	• Colectomy • Low Anterior Resection	• Rectal cancer • +access	• Fixed patient position	• May be + over laparoscopic in complex cases	22;48

Table 1: Example procedures performed using the *da Vinci* Surgical System (↑=increase, + =improve, ↓=decrease, - =reduce, EBL= estimated blood loss, OT&C=operating time & costs, NSCB=no [statistically] significant clinical benefit, CtOC=conversion to open case).

A consistent theme in the literature covering RASD technology is its association with both reduced blood loss and decreased postoperative recovery time. Other potential benefits include increased precision and accuracy of motion and access to confined surgical sites. Many researchers cite higher monetary costs and increased operating times associated with RASD technology as potential disadvantages. Complication rates vary by procedure, but, with exceptions, overall appear to be acceptably low as compared to conventional methods.[2;3;18-21]

SPECIALTY-SPECIFIC CONSIDERATIONS

The following sections provide an overview of the clinical literature concerning RASD and are intended to paint a broad picture of the use, reporting, and outcomes of RASD in a variety of surgical procedures. The sections below identify topics whether related to operative risk or to specific operative procedures from the perspective of various specialties more commonly affected by RASD use. The goal is to highlight some selected, key issues in order to stimulate robust discussion concerning the scientific challenges and opportunities associated with RASD.

The literature cited is a selection of high-level meta-analyses and review papers.

ANESTHESIA

Anesthesia considerations apply to most RASD procedures because of the current bulky nature of the equipment. Some potential challenges include patient positioning, monitoring, and access. In some surgical specialites, unique challenges may arise. For example, in cardiothoracic surgery, anesthesia issues include lung isolation techniques and transesophageal echocardiography (TEE). Complications from one‑lung ventilation include hypoxia and hypercapnia, capnothorax, percutaneous cannulation for cardiopulmonary bypass, TEE guidance, as well as methods of intraoperative monitoring and analgesia. Management of ventricular fibrillation is challenging since internal defibrillation is not possible, and chest compressions are difficult to perform.[49;50] In general, patient positioning must be carefully performed prior to placement of the RASD because of the very limited ability to reposition the patient once the device is in place. Extreme positioning (e.g. Trendelenburg / reverse Trendelenburg) combined with pneumoperitoneum can cause endotracheal tube migration.[51]

GENERAL SURGERY

Comparing the safety and effectiveness of the *da Vinci* Surgical System and conventional laparoscopic surgery (CLS) in different types of abdominal intervention, *da Vinci* was found to be associated with fewer Heller myotomy-related perforations, a more rapid intestinal recovery time after gastrectomy and a shorter hospital stay.[52;53] For Nissen fundoplication, there were no significant differences in outcomes, including post- operative dysphagia, intra-operative conversion, re-operation, hospital stay and in-hospital costs.[54] One prospective clinical trial comparing robotically-assisted and standard laparoscopic cholecystectomy found no clinical benefits to substantiate the use of such expensive technology.[55]

RASD simplify microsurgical dissection of the hepatic pedicle and biliary reconstruction, which may be challenging steps in standard laparoscopy.[56;57] However, the current experience with robotic-assisted liver resection is limited to several hundred procedures worldwide. Living donor RASD nephrectomy has been safely performed at a single center in over 700 patients with complications being associated with the device learning curve, e.g. inadequate vessel ligation or accidental laceration and chyloperitoneum. Post-operatively, bowel obstructions caused by adhesions were noted in some cases.[58] Robotically assisted pancreatico-duodenectomy (PD) is feasible and safe. Preliminary comparisons with open PD favored robotics in terms of shorter operating times, reduced blood loss and a greater number of harvested nodes.[59] Robotic-assisted adrenalectomy can be performed with operative time and conversion rates similar to laparoscopic

adrenalectomy.[60] In addition, it can provide potential advantages of a shorter hospital stay, less blood loss, and lower occurrence of postoperative complications. In bariatric surgery, the major strength of RASD technology is facilitating some of the technical steps (gastro-jejunostomy and jejunostomy anastomosis) in the robotic Roux-en-Y gastric bypass or the vertical gastric resection in the robotic sleeve gastrectomy.[52;53] Robotic-assisted incisional hernia repair with mesh has been reported to be safe but evaluation with long term data is needed.

CARDIOTHORACIC SURGERY

Robotically-assisted techniques have been developed for coronary revascularization, mitral valve repair, and atrial septal defect repair. Early attempts to translate the success of endoscopic techniques in general surgery to the field of cardiothoracic surgery had limited success due to limitations with conventional laparoscopic instruments operating in relatively narrow/confined thoracic cavities.[61] The surgical instruments of the *da Vinci* system are generally smaller than conventional laparoscopic instruments. When combined with 3D endoscopic view from the *da Vinci* system and the additional degrees of freedom afforded by the robotic technology, the system allows complex endoscopic surgical manoeuvers, such as sewing a vascular micro-anastomosis.[18] In coronary artery bypass graft (CABG) surgery, both internal mammary arteries can be harvested completely endoscopically while graft-to-coronary anastomosis is carried out through an adjunctive mini-thoracotomy, or by totally endoscopic CABG (TECABG). Experienced surgeons can perform single-vessel and double-vessel robotically-assisted CABG surgery in a reproducible manner.[62;63] Triple and quadruple endoscopic CABG surgery is currently in development.[64;65] However, increased mortality and morbidity with multivessel TECABG in beating hearts compared with expected clinical outcomes from conventional CABG surgery have been reported.[66]

The advantages of using a RASD for CABG also carry over to robotically-assisted mitral valve repair. Compared to conventional laparoscopic techniques, the *da Vinci* system offers direct view of the valve anatomy and pathology, maneuverability of the endoscopic instruments and surgeon comfort when performing complex mitral valve repair in bi-leaflet prolapse. Robotically-assisted surgery is a viable option for the majority of patients with repairable mitral valve pathology in the hand of experienced surgeons. Conversion to larger incisions is low (3.0-4.3%),[67-69] repair success seems to be excellent with a rate of residual mitral regurgitation greater than trace of 2.3-2.8%,[68;70] and perioperative mortality is 0-1%.[70-72] The main disadvantages of robotically-assisted mitral valve repair are the high system cost and longer operative times. Median cardiopulmonary bypass time was 42 minute longer than with sternotomy, 39 minutes longer than with partial sternotomy, and 11 minutes longer than with anterolateral minithoracotomy; median hospital stay, however, was 1.0, 1.6, and 0.9 days shorter using robotics than with the other three techniques, respectively.[73] The first series of robotically-assisted endoscopic atrial septal defect repair was performed in 2001.[74] Presently, totally endoscopic robotically-assisted atrial septal defect repair for overall conversion rate to larger incisions is 5%, and perioperative mortality in these series is 0%.[40;42-44;75-78] While the *da Vinci* system has not been cleared for laparoscopic vascular surgery, robotic procedures have been reported in literature based mostly on Outside of U.S. (OUS) experiences. Iliofemoral and aortofemoral bypass are the most

common types of robotically-assisted vascular reconstruction. Abdominal aortic aneurysm (AAA) repair was reported in 2010.[79] AAA repair-related outcomes were not reported.

GYNECOLOGY

In gynecological procedures, RASD technology has been adopted in several applications such as hysterectomies, myomectomies, adnexal surgery, tubal anastomosis, sacrocolpopexies and fistula repairs.[35] However, RASD technology has the highest use in gynecologic oncology where procedures such as [radical] hysterectomies, lymphadenectomies, and staging and debulking of ovarian cancer.[35;80] As in other surgical specialties, there have been no well controlled clinical studies comparing the safety and efficacy of RASD procedures to traditional laparoscopic procedures, but there is a plethora of anecdotal and single site data.[6;35;80] Additionally, reports indicate that RASD technology is most beneficial to less experienced gynecological surgeons.[35]

Generally, gynecological studies do not describe a significant advantage of RASD procedures over laparoscopic procedures, but they do tend to note decreased estimated blood loss, decreased postoperative pain and recovery times, and increased operating time and costs.[6;35] Compared to open and laparoscopic hysterectomy, RASD technology is associated with decreased blood loss, surgical complications and length of hospital stay.[6;35;80] One study reported a slight risk of dehiscence of the vaginal cuff in RAS hysterectomy.[81] For sacrocolpopexy procedures, RAS technology appears to be advantageous to less experienced surgeons due the complexity of the procedure.[35] In one study, the authors noted that the lack of haptic feedback made placement of vaginal and sacral sutures more difficult with RASD technology as compared to laparoscopy.[82]

In staging of uterine cancer, a review of 1000 single center cases indicated that RASD technology appeared to offer improved visualization and, again, shorter learning curves, which translated to decreased operating times and complication rates.[83] Like laparoscopy, RASD technology offers an advantage over open surgery for cancer staging. In myomectomies, an open approach is still preferred due to the extensive suturing of the myoma bed and uterine serosa required, as well as the dissection and removal of the myomas.[35] In one study comparing open, laparoscopic and RASD myomectomy, although RASD technology allowed performance of open-like maneuvers, there was no clear advantage associated with RASD technology over the other approaches.[84]

UROLOGY

Urology has become the largest clinical area for the *da Vinci* Surgical System, with prostatectomies the most common robotic procedure.[41] Other urological procedures frequently performed robotically include cystectomies, pyeloplasties, and partial nephrectomies. Most operative, intermediate term oncologic, functional, and complication outcomes are similar between open radical cystectomy (ORC) and Robotically Assisted Radical Cystectomy (RARC). RARC consistently results in less blood loss and a reduced need for transfusion during surgery. RARC generally requires longer operative time than ORC and appears to be similar to ORC in terms of operative, pathologic, intermediate-term oncologic, complication, and most functional outcomes. A notable disadvantage of robot-assisted radical prostatectomy is the lack of tactile

feedback; however; with experienced surgeons RARC has a slight decrease in major complications compared to open procedures.[16;41;85-89]

OTORHINOLARYNGOLOGY

The use of *da Vinci* surgical system for TORS is rapidly increasing as it offers access to many confined anatomic locations with otherwise restricted access via a natural orifice that previously required open approaches. Challenges of traditional transoral surgery include limited functionality of long instruments, poor visualization from a microscope external to the oral cavity, and impeded use of lasers removed from the target. Development of TORS has resulted in initial favorable outcomes of reduction in tracheostomy, percutaneous gastrostomies (PEG), and less over all morbidity, particularly for head and neck cancer when compared to open surgeries and chemo radiation treatments. While literature supports the use of TORS in many Head and Neck sub-sites, challenges remain of using large size of arms, current inability to use CO_2 laser via *da Vinci*, and significant thermal damage resulting from monopolar electrocautery as the primary cutting and ablating instruments. TORS may be of significant benefit to patients in terms of decreased morbidity.[90;91] In TORS procedures, dental injury is a not uncommon complication.[91]

COLORECTAL SURGERY

For colonic resection, there appears to be no benefit from robotic assistance compared with standard laparoscopy in procedures for both malignant and benign disease. For rectal resection, there is evidence that robotic assistance reduces the rate of conversion to open surgery. No differences were found in duration of surgery, morbidity, length of hospital stay or oncological outcomes.[22;54]

EMERGING APPLICATIONS

Robotics provide a platform for innovative solutions to new and emerging clinical challenges.[16] For example one group is investigating robotic solutions for transurethral bladder tumor resection.[92] Single port access surgery, often referred to as laparoscopic endoscopic single site surgery (LESS), is emerging and the development of concentric tube robots and steerable needles continues. Miniaturization, improved control, and haptics will improve the utility of RASD.

In the arena of artificial sensors, new imaging modalities are being developed and incorporated into surgical practice. Some of these modalities involve the use of near-infrared imaging, confocal microscopy, intraoperative ultrasound, Raman spectroscopy, biomarkers, dyes, and autofluorescence to improve identification of tissues, such as nerves, blood and lymphatic vessels, and malignancies. Silica-gold nanoparticles that specifically target breast cancer with the design to be used for intraoperative detection of tumor margins are also being developed. With robotic devices, these additional imaging modalities can be integrated with the surgeon's display, similar to a heads-up display used in military aircraft with the goal of making surgeries safer and more effective with decreased patient morbidity and improved oncologic resections.[2;3;92] With the far-reaching scope of RASD, FDA seeks collaborative and scientific discussions among all

stakeholders (clinicians, academia, industry, etc.) to encourage innovation while ensuring safe and effective use of these products.

4. TRAINING REVIEW

CURRENT PARADIGMS

Currently, there is no standardized credentialing system for evaluating a surgeon's proficiency for performing RASD procedures.[93] However, a few medical societies have expressed their views on training and credentialing. In 2007, the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) collaborated with the Minimally Invasive Robotic Association (MIRA) to publish a consensus document on robotic surgery.[94] This document recommended guidelines for granting and maintaining robotic surgery privileges. It also established recommendations for robotic surgery training, including didactics, live case observation, and hands-on training involving medical simulation.

Due to the prevalence of robotically-assisted urological procedures, the Society of Urological Robotic Surgeons has developed specific recommendations for safe proctoring and privileging of robot-assisted radical prostatectomies.[93] Likewise, the American Urological Association (AUA) now includes robotically-assisted surgery in its Core Curriculum for urology residencies. As described in the AUA's Standard Operating Practices for Urological Robotic Surgery, those who have been exposed to robotic surgery training in their residency or fellowship must provide evidence of experience with a minimum of 20 robotic cases. For urologists with no residency or fellowship experience in robotics, the AUA recommends a structured training program that includes a combination of online courses, observation of robotic surgeries, hands-on experience, and assistance from experienced robotic surgeons.

Several institutions that have already successfully established robotic training programs, have been willing to share best practices learned from their experiences. For example, Tacoma General Hospital has based their robotic training program on an aviation training model.[95] University of California, Irvine has developed a two-stage approach with recommendations for preclinical and clinical components.[96]

SIMULATORS

One of the biggest barriers to training for residents and attending surgeons is the availability of a RASD, even in a teaching hospital. It has been theorized that training on simulators may help remove this barrier and shorten the learning curve for surgeons learning to use RASD.[97] Current commercially-available surgical simulators include the *da Vinci* Skills Simulator, RoSS, dV-Trainer, SEP-Robot, and RobotiX Mentor.

1. Intuitive Surgical's Skills Simulator is a portable modular simulator that can be mounted on an existing *da Vinci* surgeon console. The Skills Simulator contains a

variety of exercises ranging from basic setup and instrument manipulation to knot tying and suturing. It also possesses the ability to provide real-time feedback and track user progress.

2. The Robotic Surgical Simulator (RoSS), developed by Simulated Surgical Systems, is a portable, stand-alone robotic surgery simulator. Through a multi-level curriculum, the RoSS uses virtual reality to teach novice surgeons the basic skills required for operating the da Vinci Surgical System. The RoSS also contains a unique feature called "Hands-on Surgical Training" that allows the user to practice specific surgical tasks during an interactive video of a surgery.[98]

3. The dV-Trainer is a standalone, desktop robotic simulator developed by MIMIC Technology. The Maestro AR is augmented reality software recently launched by MIMIC Technology that is available exclusively on the dV-Trainer. This software allows users to manipulate virtual instruments within a 3D anatomical environment. It helps users to identify anatomic regions, anticipate tissue retractions, and predict areas for dissection. The Maestro AR also possesses the ability to simulate specific surgical procedures, including nephrectomy, hysterectomy, low anterior colon resection, and prostatectomy.[99]

4. The SimSurgery Education Platform Robot (SEP-Robot) is a robotic simulator developed by Norwegian company, SimSurgery. It consists of a console connected to 2 instruments, each with 7 degrees of freedom. Although the SEP-Robot does not provide 3 dimensional images, the simulator does allow the trainee to perform basic surgical tasks such as object manipulation and suturing.[100]

5. The RobotiX Mentor is a robotic simulator developed by Simbionix. In addition to teaching basic skills, it provides simulated cases of complete robotic procedures such as vaginal cuff closure and hysterectomy. It also simulates emergency situations and complications, and provides an option for team-based training. [99]

While FDA does not regulate medical simulators as medical devices, the Agency is interested in the development of such medical device development tools (MDDT) and would be interested in working with RASD developers to validate the use of surgical simulators as an MDDT. Ideally, a surgical simulator should be able to teach and assess surgical skills effectively, and to provide a realistic representation of a surgery. It should possess enough sensitivity to distinguish between surgeons of various skills levels. The results of the simulated surgery should correlate well with a real surgery, and these results should be predictive of future surgical performance. Finally, a simulator should be reliable in producing consistent, reproducible results.[101;102]

TRAINING AND SIMULATION CHALLENGES AND FUTURE DIRECTIONS

Presently, individual hospitals work to implement and establish training requirements in order to credential their surgeons to perform robotic surgery procedures. Because establishing a robotic surgery training program requires substantial financial investment, the quality of training programs may vary depending on the resources of each hospital. The average cost of training a surgical team on RASD procedures has been estimated to be about $10,000 per surgeon.[103] As such, it is often a challenge to balance the costs of establishing a robotic surgery program without compromising educational quality. Future direction will involve developing new educational paradigms and technologies that enable cost-effective RASD training programs.[104]

While surgical simulators are expected to play an increasingly important role in RASD training programs, they also possess their challenges. While some basic validation studies have been performed on robotic simulators, there have been very few studies demonstrating the reliability and predictive validity of these simulators.[105] In the future, further validation studies may lead to improved simulators that better suit the educational needs of robotic surgeons.

The educational content of robotic simulators is also continuing to evolve. Currently, most exercises available on robotic simulators involve generic tasks, such as tissue manipulation and suturing. While these exercises have been shown to be beneficial in the early stages of training, it has been debated whether they lead to improved performance in the surgical setting.[105] Future directions will involve developing simulated training scenarios that include procedure-specific challenges and complications.

In recent years, there has been increasing dialogue within the medical community regarding the possibility of standardizing robotic surgery training and credentialing. In 2011, 17 medical societies gathered together to discuss creation of a unified "Fundamentals of Robotic Surgery" curriculum. The participants agreed on a list of 25 outcomes to be mastered by a surgeon seeking robotic surgery privileges, including 8 pre-operative, 15 intra-operative, and 2 post-operative tasks. Through a series of conferences in 2012, the participants worked to develop a curriculum based on these 25 outcomes.[106] While questions remain on the feasibility of establishing a standardized system, efforts like this represent the initial step in identifying the aspects of training needed to ensure surgeons are sufficient to perform robotic surgery safely and effectively.

5. POST-MARKET SURVEILLANCE

CDRH has identified striking the right balance between premarket and postmarket data collection as a strategic priority to help foster the delivery of high-quality, safe and effective medical devices to patients in a timely fashion. In the postmarket arena, FDA is working on multiple fronts to strengthen the Nation's postmarket surveillance system for medical devices.

NATIONAL MEDICAL DEVICE SURVEILLANCE SYSTEM

FDA's vision for a National Medical Device Postmarket Surveillance System (MDS) is to identify poorly performing devices in near real-time; accurately characterize and disseminate

information about the real-world performance of marketed devices; and efficiently generate data to facilitate the clearance and approval of new devices, or new uses of existing devices. In 2012, FDA laid out a strategy to strengthen the MDS as a complement to recent improvements made its premarket review system.[107] In 2013, after receiving public input, FDA published an update to the 2012 plan and described the steps it would take to begin the development of an MDS that relied upon privacy-protected, routinely collected electronic health information containing unique device identifiers (UDIs) and device-specific registries in selected product areas complemented by additional data sources (e.g. adverse event reports, administrative and claims data).[108] [Figure 1]

UDI will significantly enhance postmarket surveillance activities by providing a standard and unambiguous way to document device use in electronic health records, clinical information systems, claims data sources, and registries, potentially making vast amounts of previously untapped clinical information available for assessing the benefits and risks of medical devices and more meaningfully and efficiently linking data sources (like registries and claims data). Registries can provide additional detailed information about patients, procedures, and devices not routinely collected by electronic health records, administrative or claims data.

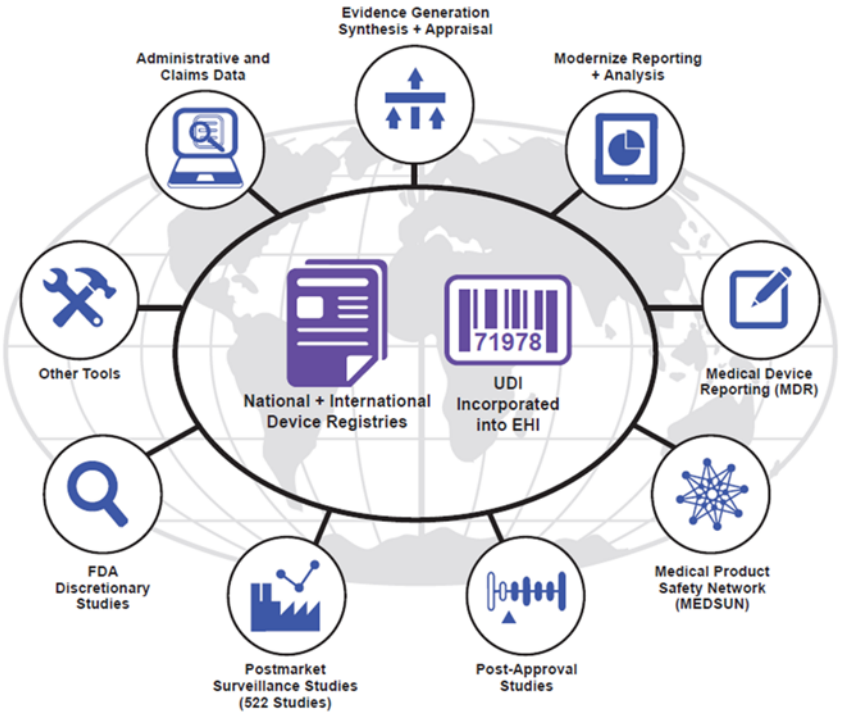

Figure 1: National Medical Device Surveillance System

FDA has made significant progress in laying the groundwork for this national system. The Engelberg Center for Health Care Reform at the Brookings Institution convened and oversaw deliberations of the MDS Planning Board resulting in the 2015 release of the Planning Board's report *Strengthening Patient Care: Building an Effective National Medical Device Surveillance*

System, which outlines recommended steps toward achieving the MDS and strategies for implementation.[109] Phased implementation of 2013 Unique Device Identification rule has begun, including development of a Global UDI Database (GUDID) as the repository for information that unambiguously identifies devices through their distribution and use. FDA also continues to build medical device registry capabilities both domestically and internationally.

The efforts being made to strengthen the MDS will complement the postmarket surveillance authorities and approaches that FDA has traditionally relied upon. [Table 2]

Medical Device Reporting (MDR)[110]: Each year, the FDA receives several hundred thousand medical device reports of confirmed or possible device-associated serious injuries, deaths, and malfunctions. MDRs are used to monitor device performance, detect potential device-related safety issues, and contribute to benefit-risk assessments of these products. Although MDRs are a valuable source of information, this passive surveillance system has limitations, including under-reporting, and the potential submission of incomplete, inaccurate, untimely, unverified, or biased data. In addition, the incidence or prevalence of an event cannot be determined from this reporting system alone due to lack of information about frequency of device use (denominator data).
Medical Product Safety Network (MedSun)[111]: MedSun is an enhanced surveillance network comprising approximately 250 hospitals nationwide that work interactively with the FDA to better understand and report on device use and adverse outcomes in the real-world clinical environment. In addition, the network is used for targeted surveys and focused clinical research.
Postmarket Surveillance Studies[112]: The FDA may order a manufacturer of certain Class II or Class III devices to conduct postmarket surveillance studies (often referred to as "522 studies" for section 522 of the Food, Drug and Cosmetic Act). Study approaches vary widely and may include non-clinical device testing, analysis of existing clinical databases, observational studies, and, rarely, randomized controlled trials. CDRH maintains a list of 522 studies.[113]
FDA Discretionary Studies: In addition to medical device adverse event reports, post-approval and postmarket surveillance studies, the FDA can conduct its own research studies to assess device performance and clinical outcomes, investigate adverse event signals and characterize device-associated benefits and risks for patient sub-populations. A variety of privacy-protected data sources are used including national registries, Medicare and Medicaid administrative and claims data, data from integrated health systems, electronic health records, and published scientific literature.
Post-Approval Studies[114]: The FDA may order a post-approval study as a condition of approval for a device approved under a premarket approval (PMA) order. Typically, post-approval studies are used to assess device safety, effectiveness, and/or reliability in the real-world setting,

including long-term effects. The PAS can also be used to assess the learning curve, effectiveness of training programs and how well device performs in certain groups of patients. CDRH maintains a list of post-approval studies[115]. Since RASD currently are not approved through the PMA process, this information on Post Approval Studies has been added to show a complete picture of FDA post market controls.

Table 2: Existing FDA postmarket authorities and approaches

ADDITIONAL POST-MARKET SURVELLIANCE

There exists a large amount of clinical literature for RASD, including more than 8,000 peer-reviewed publications[116]. Publications range from reports of randomized controlled trials to single case reports and often lack long term follow up on patients. The development of national and international registries of RASD may offer an opportunity to supplement the information available in literature reports and streamline the collection of postmarket clinical data when needed, In addition, such infrastructure could potentially be leveraged to support regulatory submissions for new or modified devices and to develop and assess new uses of RASD. FDA recognizes that the development of such infrastructure can be costly and resource intensive. However, several collaborative efforts between FDA, professional medical societies, industry and other stakeholders related to other medical devices have been successful.

In absence of a RASD registry, there is a need to collect and analyze existing information to advance our understanding of RASD safety and effectiveness. During the past several years FDA invested strategic efforts in the development of Medical Device Epidemiology Network Initiative (MDEpiNet) public-private partnership established to advance the national/international infrastructure and novel analytic approaches that will bridge the evidentiary gaps in the life cycle of medical device innovation, evaluation and surveillance.[117] With over 40 organizations actively participating, MDEpiNet had been a platform for over 50 ongoing studies advancing registry development, linkage of various data sources, evidence synthesis, big data analytics, implementation of UDI, active surveillance, etc. MDEpiNet infrastructure and methodological capabilities can potentially be leveraged to include RASD evidence evaluation.

While data collection and analysis is necessary, the method by which data reporting is performed could also be strengthened. The IDEAL (Idea, Development, Exploration, Assessment, Long-Term Follow-up) Collaboration grew out of a recognition that there exists an opportunity to improve the quality of research in surgery.[118] This group has proposed the IDEAL framework for describing the stages of development of surgical and interventional innovations and recommendations about how methodology and reporting of research at each of these stages could be improved (Table 3). The group has also proposed for stakeholders to work together to change the environment for this kind of research in a positive manner. In 2010 the idea of introducing a medical device dimension to the IDEAL framework was introduced and then further developed in collaboration with FDA.[119]

Phase 1 IDEA	Phase 2a DEVELOPMENT	Phase 2b EXPLORATION	Phase 3 ASSESSMENT	Phase 4 LONG TERM MONITORING
Professional Innovation Database	***Prospective Development Studies***	***Phase IIS Study***	***Surgical RCT***	***Prospective Registries***
Initial report **Innovation may be planned, accidental or forced** **Focus on explanation and description**	"Tinkering" (rapid iterative modification of technique and indications) Small experience from one centre Focus on technical details and feasibility	Technique now more stable Replication by others Focus on adverse effects and potential benefits Learning curves important Definition and quality parameters developed	Gaining wide acceptance Considered as possible replacement for current treatment Comparison against current best practice	Monitoring late and rare problems, changes in use

Table 3. IDEAL Framework

6. CONCLUSION

There are scientific, clinical, and regulatory challenges associated with creating a balanced and scientifically sound evidentiary framework for evaluating RASD. Different surgical specialties may see RASD as providing different benefit/risk profiles for their patients, and therefore may have different evidentiary requirements.

There is also great opportunity for engaging all stakeholders to progress thinking about the operating room environment as a system and for using a systems approach for maximizing benefit and minimizing risks associated with RASD procedures. Considering RASD as a component of a system (i.e. other components include the entire operating room team, all concurrently used medical devices, and the patient) rather than an isolated medical device will allow us to fully realize RASD potential for surpassing current surgical capabilities.

We identified the following challenges and opportunities that may be considered when striving to optimize patient care through the use of RASD:

- What are the key fundamental technological and performance characteristics for a new RASD platform? What are the key fundamental technological and performance characteristics for iterative changes to marketed RASD platforms?
- How should interoperability among RASD platforms and other medical devices intended for use with those platforms (including those from different manufacturers) be assessed? What sort of evidence, if any, should be provided? Should interoperability be promoted?
- When are the considerations when distinguishing between "general" use indications and "specific" indications for RASD? Under what circumstances are additional data needed?
- What is the role of training and simulation during the premarket evaluation as a means for ensuring device usability and mitigating risk? How should it be assessed?
- How can collaboration among all stakeholders be promoted to improve and create data sources that can be efficiently leveraged for multiple purposes.

We hope that this paper has provided the context and basis for robust discussions at FDA's July 27-28, 2015 RASD Workshop. We look forward to working together to excel RASD technology in a way that makes sense, mitigates risk, and provides value in terms of patient benefit to the American public.

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