Week 1 – Robotic-assisted Laparoscopic Surgery and Intraluminal Robotics

ELEC0145 Robotics in Medicine and Industry

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Acknowledgement

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  - Dr. Agostino Stilli
  - Dr. Lukas Lindenroth
  - Dr. Joao Ramalhinho
  - Claudia D’Ettorre
- from the Medical Physics and Biomedical Engineering Department for providing the contents of the slides.

Schedule

Week	Lecture (L) / Workshop (W)	Assignment Deadlines
1	L: Introduction; Robotics-Assisted Laparoscopic Surgery and Intraluminal Robotics	
2	L: Rehabilitation, Assistive and Prosthetic Robotics	
3	L: Robotic-assisted Orthopaedic Surgery and Intervention	
4	L: Continuum Robotics for Transluminal Surgery and Intervention	
5	L: Medical Devices Regulations	
RW		Design of Medical Robots
6	W: Industrial Challenge Provided	
7	W: Solve Industrial Challenge	
8	W: Solve Industrial Challenge	
9	W: Solve Industrial Challenge	
10	W: Present Solution to Industrial Challenge	Report of Industrial Challenge

Content

- A Brief History of Medical Robotics
- ZEUS vs da Vinci
- Autonomy in Medical Robotics
- Minimally Invasive Robotic Surgery Classification
  - Extraluminal Procedures
  - Intraluminal Procedures
  - Transluminal Procedures
  - Hybrid Procedures
- Case Study – Robotic-assisted Colonoscopy

Relevant Literature (1)

- T. Lane, **“A short history of robotic surgery,”** Ann. R. Coll. Surg. Engl., vol. 100, no. 6_sup, pp. 5–7, 2018.

- E. I. George, T. C. Brand, A. LaPorta, J. Marescaux, and R. M. Satava, **“Origins of Robotic Surgery: From Skepticism to Standard of Care,”** JSLS J. Soc. Laparoendosc. Surg., vol. 22, no. 4, 2018.

- M. L. Lorentziadis, “**A short history of the invasion of robots in surgery**,” Hell. J. Surg., vol. 86, no. 3, pp. 117–121, 2014.

- P. P. Rao, **“Robotic surgery: new robots and finally some real competition!,”** World J. Urol., vol. 36, no. 4, pp. 537–541, 2018.

- A. Brodie and N. Vasdev, **“The future of robotic surgery,”** Ann. R. Coll. Surg. Engl., vol. 100, no. Supplement 7, pp. 4–13, 2018.

- K. H. Sheetz, J. Claflin, and J. B. Dimick, **“Trends in the Adoption of Robotic Surgery for Common Surgical Procedures,”** JAMA Netw. Open, vol. 3, no. 1, pp. e1918911–e1918911, 2020.

Relevant Literature (2)

- G. Z. Yang et al., **“Medical robotics-Regulatory, ethical, and legal considerations for increasing levels of autonomy,”** Sci. Robot., vol. 2, no. 4, p. 8638, 2017.

- V. Vitiello, S.-L. Lee, T. P. Cundy, and G.-Z. Yang, “**Emerging robotic platforms for minimally invasive surgery**,” IEEE Rev. Biomed. Eng., vol. 6, pp. 111–126, 2012.

- P. E. Dupont et al., “**A decade retrospective of medical robotics research from 2010 to 2020**,” Sci. Robot., vol. 6, no. 60, p. eabi8017, 20

- G. Ciuti et al., “**Frontiers of robotic colonoscopy: a comprehensive review of robotic colonoscopes and technologies**,” J. Clin. Med., vol. 9, no. 6, p. 1648, 2020.

- W. Marlicz et al., “**Frontiers of Robotic Gastroscopy: A Comprehensive Review of Robotic Gastroscopes and Technologies**,” Cancers (Basel)., vol. 12, no. 10, p. 2775, 2020.

- G. Ciuti et al., “**Frontiers of robotic endoscopic capsules: a review**,” J. micro-bio Robot., vol. 11, no. 1, pp. 1–18, 2016.

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A Brief History of Medical Robotics (1)

- Initially, used industrial robots for medical procedures.
- 1988: Kwoh et used the PUMA 560 robotic system to undertake neurosurgical biopsies with greater accuracy.
  - In effect, stereotactic brain surgery [Ref1].
  - Stereostatic means accurate positioning of probes inside the brain or other parts of the body.

Figure 1: Puma 200 Surgical Robot [Ref2]

Ref1: Y. S. Kwoh, J. Hou, E. A. Jonckheere, and S. Hayati, "A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery," IEEE Trans. Biomed. Eng., vol. 35, no. 2, pp. 153–160, 1988.
Ref2: M. L. Lorentziadis, "A short history of the invasion of robots in surgery," Hell. J. Surg., vol. 86, no. 3, pp. 117–121, 2014.

A Brief History of Medical Robotics (2)

- 1991: The same system was subsequently used by Prof. Brian Davies (ICL) et al to undertake a Transurethral Resection of the Prostate (TURP)
  - Access prostate through urethra, cut the prostate using a single tool, then remove piece-by-piece via the urethra.
  - Need a lot of dexterity as well as precision.
  - Need to make sure no cancer cell left behind.
  - And also need to make sure nothing beyond the prostate wall is damaged.
  - Note: The procedure itself is not new, but robotics provide higher accuracy.

A Brief History of Medical Robotics (3)

- (Continued)
- a precursor of what would ultimately be termed the PROBOT - developed by Integrated Surgical Supplies Ltd.
- In essence, the PROBOT represented a framework to direct a rotating blade to complete the process of prostatic resection. [Ref1]

Ref1: B. L. Davies, R. D. Hibberd, W. S. Ng, A. G. Timoney, and J. E. A. Wickham, “The Development of a Surgeon Robot for Prostatectomies,” Proc. Inst. Mech. Eng. Part H J. Eng. Med., vol. 205, no. 1, pp. 35–38, 1991.

A Brief History of Medical Robotics (4)

- 1992: The ROBODOC system was the first of the active robotic systems to achieve a formal FDA approval.
  - This was a machine designed to improve the precision of hip replacement surgery.
  - It was adopted almost immediately in Europe (1994) (and subsequently in the US), with the first procedures being undertaken in 1992.
  - Preliminary studies related to ROBODOC started already in 1986. [Ref2]

Figure 1: RoboDoc Surgical System [Ref1]

Ref1: M. L. Lorentziadis, “A short history of the invasion of robots in surgery,” Hell. J. Surg., vol. 86, no. 3, pp. 117–121, 2014.
Ref2: W. L. Bargar, A. Bauer, and M. Börner, “Primary and revision total hip replacement using the ROBODOC® system,” Clin. Orthop. Relat. Res., vol. 354, pp. 82–91, 1998.

A Brief History of Medical Robotics (5)

- 1998: A research group at Johns Hopkins Medical Center developed a robot called PAKY (Percutaneous Access to the Kidney)

  - Employed a percutaneous (passing through the skin) approach to access the kidney for stone surgery [Ref1]
  - This has basically paved way for many other surgical robotic systems, because of similar the type of access required.

Ref1: J. A. Cadeddu, D. Stoianovici, R. N. Chen, R. G. Moore, and L. R. Kavoussi, “Stereotactic mechanical percutaneous renal access,” J. Endourol., vol. 12, no. 2, pp. 121–125, 1998.

A Brief History of Medical Robotics (6)

- The early active robotic systems clearly demonstrated the potential of mechanical devices to enhance surgical interventions.

- However, the driving force for developments that were ultimately to enhance laparoscopic procedures (e.g. Da Vinci) were based on the concept of telepresence.

A Brief History of Medical Robotics (7)

- Telepresence in turn was derived from a collaboration between the Ames Research Centre at NASA and researchers from Stanford.
  - The robotics components of early telepresence surgery came from Phil Green, PhD, of Stanford Research Institute (SRI, later SRI International), a civilian institute with a federally funded research and development center (FFRDC).
  - In 1987 US Army Colonel (COL) Richard Satava, MD, joined the team as SRI began construction of the first prototype of a robotic surgery system, which Dr. Green called the “telepresence surgery system”.

A Brief History of Medical Robotics (8)

- The first constructed prototype (Figure 1) consisted of 2 discrete units: the Telepresence Surgeon's Workstation (TSW) and a Remote Surgical Unit (RSU).

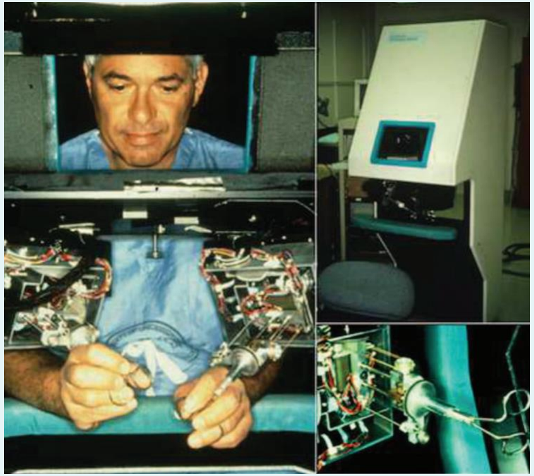

Figure 1:

- (left) COL Anthony LaPorta operating the telepresence surgeon's workstation (TSW).
- (top right) Early version of the TSW (note the ergonomic design, adjustable stool, and armrest to stabilize and rest the arms).
- (Bottom right) TSW master controls, reengineered from a standard surgical instrument. [Ref1]

Ref1: E. I. George, T. C. Brand, A. LaPorta, J. Marescaux, and R. M. Satava, "Origins of Robotic Surgery: From Skepticism to Standard of Care," JSLS J. Soc. Laparoendosc. Surg., vol. 22, no. 4, 2018.

A Brief History of Medical Robotics (9)

- (Continued)
- The system was originally conceived for open surgery.
- COL Satava argued that the telepresence system offered a solution through the use of robotic instrumentation that solved the problem of the fulcrum effect of traditional laparoscopic tools.
- In addition, it provided a full high-definition stereoscopic vision, enhanced dexterity, tremor reduction, and motion scaling that could improve a surgeon’s performance, even beyond human physical limitations.
- The first manipulators used by SRI were patented in 1995 and continued by Dr. Green in 1998.

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Zeus vs Da Vinci (1)

- Direct funding was provided to Computer Motion to develop the Automated Endoscopic System for Optimal Positioning (AESOP) robotic platform.
  - In 1996 the AESOP system received F.D.A approval and was accepted by the surgical community.
  - The robot reduced the number of surgical assistants by one and offered a steadier endoscopic view.
  - The first robot in general surgery had become a reality.

Figure 1: AESOP (Automatic Endoscopic System for Optimal Positioning) [Ref1]

Ref1: M. L. Lorentziadis, “A short history of the invasion of robots in surgery,” Hell. J. Surg., vol. 86, no. 3, pp. 117–121, 2014.

Zeus vs Da Vinci (2)

- AESOP essentially enabled surgeons to voice control the positioning of a laparoscopic camera system.
  - Voice control not popular anymore nowadays – can be quite chaotic in surgical theatre.
  - However, this system powered the research effort in the Zeus system, which basically is an integration of the AESOP system with two robotic arms (see next page).

Zeus vs Da Vinci (3)

- In 1998, Computer Motion (Goleta, CA, US) presented another robotic system called ZEUS.
  - This system consisted of an AESOP robotic camera holder combined with two additional robotic arms.
  - The first generation of ZEUS only allowed 2-D vision while the second-generation system offered 3-D glasses.

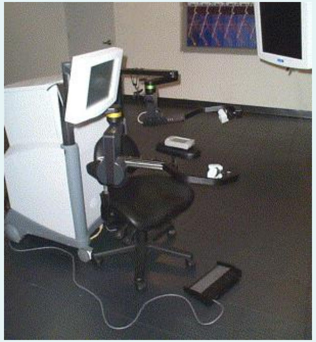
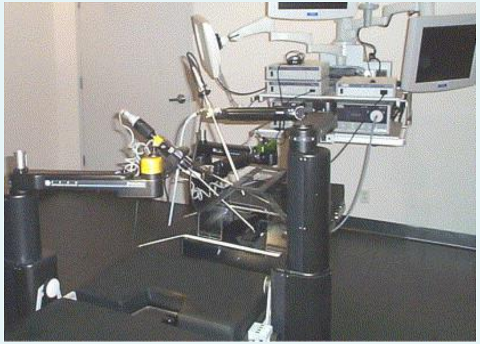

Figure 1: First Generation ZEUS master-slave system.

- Master console (left): The surgeon views the operative field on a flat screen. The robotic arms are controlled using form-fitted handles at the end of the armrest.
- Slave system (right): Three robotic arms are mounted onto the operating room table and controlled from the console. [Ref1]

Ref1: H. L. Kim and P. Schulam, “The PAKY, HERMES, AESOP, ZEUS, and da Vinci robotic systems,” Urol. Clin., vol. 31, no. 4, pp. 659–669, 2004

Zeus vs Da Vinci (4)

- Meanwhile in 1995, Frederick Moll M.D., a medical device developer and entrepreneur from Silicon Valley, acquired the licensed rights to S.R.I. Green Telepresence Surgery and founded the Intuitive Surgical INC.
  - In April 1997, this corporation presented the da Vinci® Robotic Surgical System (Figure 1).

Figure 1: The da Vinci surgical system. The surgical cart is positioned adjacent to the operating room table. [Ref1]

Ref1: H. L. Kim and P. Schulam, "The PAKY, HERMES, AESOP, ZEUS, and da Vinci robotic systems," Urol. Clin., vol. 31, no. 4, pp. 659–669, 2004

Zeus vs Da Vinci (5)

- These two rival systems, ZEUS and da Vinci®, went on to dominate the field of robotic surgery for a decade – trading world-firsts and pushing back the frontiers of minimally invasive surgery.

- The three-armed ZEUS platform continued to make use of the voice-activated AESOP camera system.
  - One of its three arms held the camera and a further two arms were used to hold surgical instruments.

Zeus vs Da Vinci (6)

- The da Vinci® platform represented a three-to-four-armed system:
  - with a central arm holding a binocular lens (for 3D vision)
  - with the surgical instruments used via the remaining arms.
  - Wrist has seven degrees of freedom.
    - More dexterity at the end-effector.
    - It represented a unique selling point and an innovation that ultimately proved crucial in the subsequent dominance of the da Vinci® platform.

Zeus vs Da Vinci (7)

- 1997 (da Vinci®): Jacques Himers M.D. and Guy Cordiere M.D. performed the first robotic surgical procedure, namely a cholecystectomy (surgery to remove gallbladder), on a patient in Brussels.
- 1998 (da Vinci®): Carpentier et al undertook a (heart) mitral valve replacement – significantly taking advantage of the innovative ‘wristed’ instruments for the first time.

Zeus vs Da Vinci (8)

- 1998 (ZEUS): Subsequently, a re-anastomosis (re-connection) of a Fallopian tube was performed.

- 1999 (ZEUS): The first closed-chest beating-heart cardiac bypass procedure was undertaken by Douglas Boyd and colleagues at the London Health Sciences Centre in Ontario.
  - The same team later went on to undertake a cardiac revascularisation (widening of blocked or narrowed coronary arteries) procedure.

Zeus vs Da Vinci (9)

- 2000 (da Vinci®): First FDA approved robotic system for general laparoscopic surgery.

- 2001 (ZEUS): Using an Asynchronous Transfer Mode (ATM) fiber optic cable, Jacques Marescaux and Michel Gagner were able to perform a transatlantic cholecystectomy
  - The operative surgeon undertaking the procedure in New York while the patient was physically in Strasbourg, France.

Zeus vs Da Vinci (10)

- 2002 (da Vinci®): FDA approved for mitral valve repair surgery.
- 2003: After a series of fierce patent infringement suits the ZEUS and da Vinci® systems were effectively unified when Computer Motion Inc. (Goleta, CA, US) and Intuitive Surgical Inc. (Sunnyvale, CA, US) merged in 2003 (at 32% to 68%).
  - As a result, further innovations and improvements were centered on the da Vinci® platform, which has subsequently dominated the world of robotic surgery for almost a decade.

Zeus vs Da Vinci (11)

- 2003-2018: The da Vinci® Surgical Robot by Intuitive Surgical Inc. (Sunnyvale, CA, US) and its various iterations (the S, Si, X and Xi) remained the predominant robot used in laparoscopic surgery.

  - This monopoly situation has led to rising costs (one system costs on average 1.5 – 2 Million $ with an average cost per use of $ 1500 [Ref1] – including cost of limited/non-reusable tools) and relatively slow innovation.

Ref1: P. P. Rao, "Robotic surgery: new robots and finally some real competition!," World J. Urol., vol. 36, no. 4, pp. 537–541, 2018.

Zeus vs Da Vinci (12)

- 2018-present: Thanks to the fact that a number of patents held by Intuitive Surgical Inc. (Sunnyvale, CA, US) expired, competition started again, and we now have multiple players trying to offer alternatives to the da Vinci® including:
  - Cambridge Medical Robotics (Cambridge, UK) with the Versius® Surgical Robotic System (approved in EU, UK, Australia and Brazil);

Zeus vs Da Vinci (13)

- (Continued)
- Verb Surgical Inc. (Santa Clara, CA, US) formed by Johnson & Johnson (New Brunswick, NJ, US) in 2015 in partnership with Verily Life Sciences LLC (South San Francisco, CA, US) – formerly Google Life Sciences, and then fully acquired by Johnson & Johnson in 2019;
- Medtronic (Dublin, Ireland) with the Medtronic Hugo™ RAS System (CE Marked, in US investigational device).
- Differentiation from Da Vinci: Multi-robotic system, with one arm on one stand. Easier to move around in surgical theatre; not all arms needed for certain procedures.

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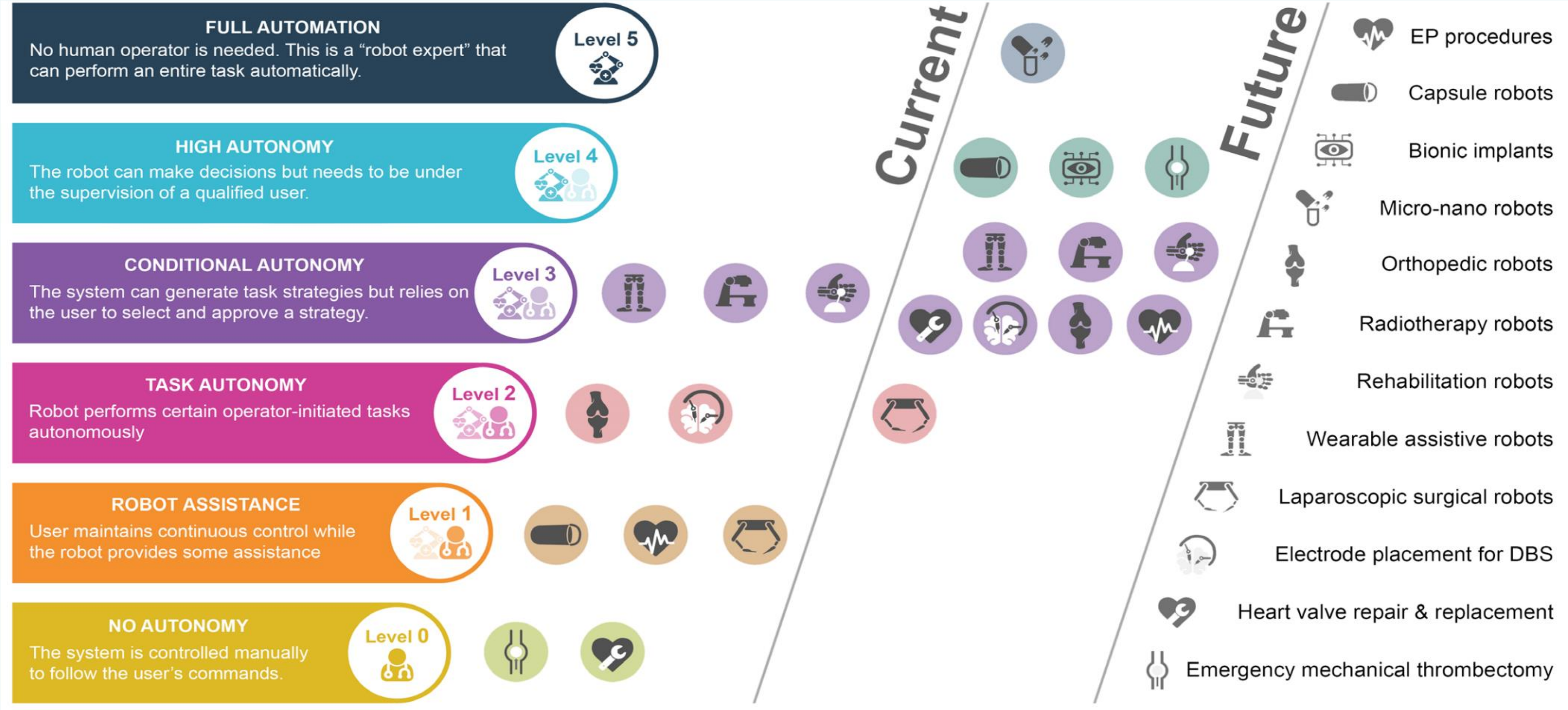
Autonomy in Medical Robotics



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Minimally Invasive (Robotic) Surgery (MIS) Development (1)

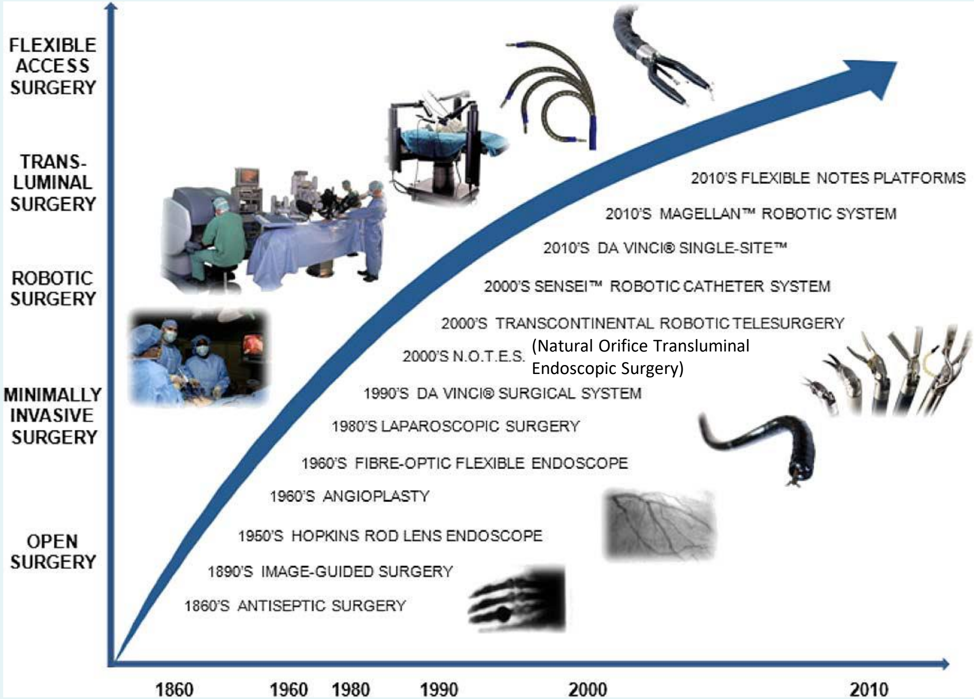

Figure 1 [Ref1]: Some of the key milestones in Minimally Invasive Surgery, image guidance and surgical technology.

- Images of laparoscopic surgery, CT scan and angioplasty can be downloaded from Wikimedia Commons and are released in the public domain.
- Image of da Vinci® surgical system and instruments (Intuitive Surgical, Inc, Sunnyvale, CA, US); image of ZEUS© system Computer Motion Inc. (Goleta, CA, US) ; image of articulated catheter [Ref2];
- Image of EndoSamurai (Olympus) [Ref3]; and image of flexible endoscope (Scope Connection).

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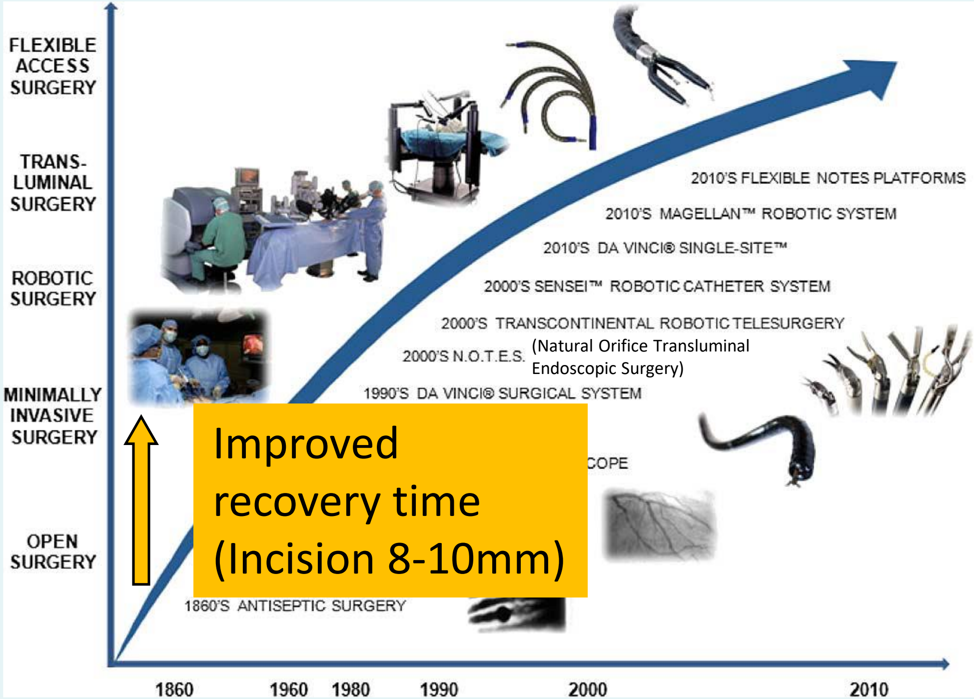
Ref2: D. B. Camarillo, C. F. Milne, C. R. Carlson, M. R. Zinn, and J. K. Salisbury, “Mechanics modeling of tendon-driven continuum manipulators,” IEEE Trans. Robot., vol. 24, no. 6, pp. 1262–1273, 2008.

Ref3: S. N. Shaikh and C. C. Thompson, “Natural orifice translumenal surgery: Flexible platform review,” World J. Gastrointest. Surg., vol. 2, no. 6, p. 210, 2010.

Minimally Invasive (Robotic) Surgery (MIS) Development (2)



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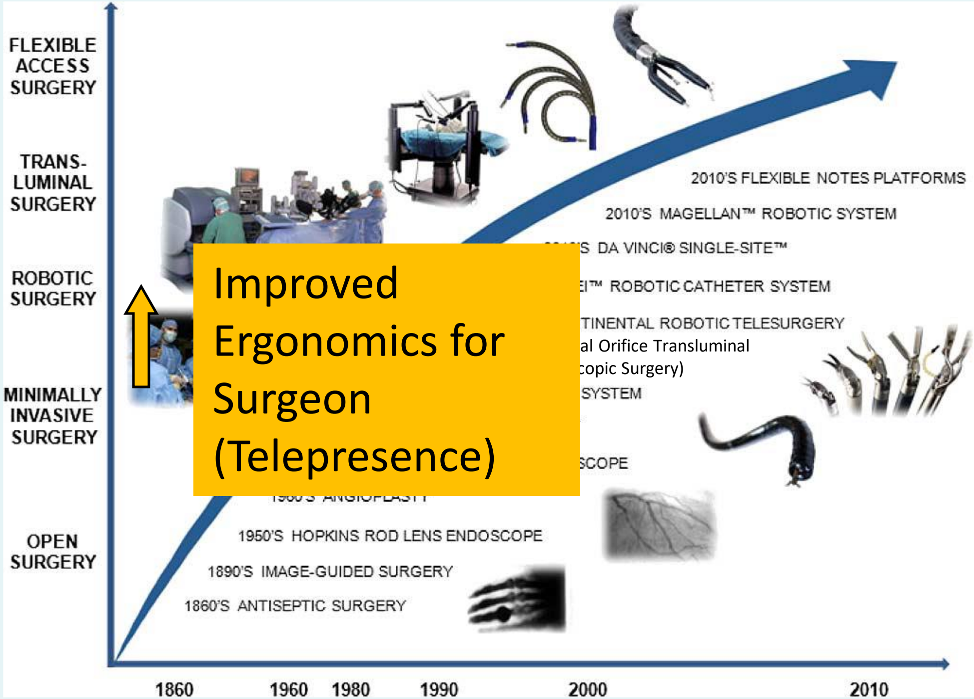
Minimally Invasive (Robotic) Surgery (MIS) Development (3)



Improved Ergonomics for Surgeon (Telepresence)

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Minimally Invasive (Robotic) Surgery (MIS) Development (4)

- The design of any MIS platform is aimed at simplifying the procedure for the surgeon.
- In particular, the fundamental clinical requirements for all minimally invasive surgical platforms are:
  - Safety
  - Effectiveness of treatment (is the procedure fast?)
  - Sound ergonomics (clinician in comfortable position? telepresence)

Minimally Invasive (Robotic) Surgery (MIS) Development (5)

- Tasks of MIS procedures include:
  - Access to a body cavity or intraluminal site;
  - Tissue dissection to expose the operative site for identification and manipulation of target tissue (e.g. take a sample);
  - Tissue destruction using focused energy delivery devices or dissection instruments for ablation, resection or excision;
  - Tissue reconstruction using techniques such as suturing or stapling (e.g. re-anastomosis of a Fallopian tube).

Minimally Invasive (Robotic) Surgery (MIS) Development (6)

- In addition, the platform should have:
  - A small footprint (space in the OR is typically an issue)
  - Enhanced dexterity, precision and stability.
  - Adequate visualization of the surgical workspace
  - Seamless visual-motor coordination (e.g. no lag).

Minimally Invasive (Robotic) Surgery (MIS) Classification (1)

- Intraluminal:
  - Procedures are performed within tubular anatomical structures, usually accessed via natural orifices.
  - Endoscopic or image-guided navigation.
  - Challenges:
    - Spatially constrained operative workspaces
    - Flexibility / dexterity for safe access and high maneuverability (e.g. long colon)

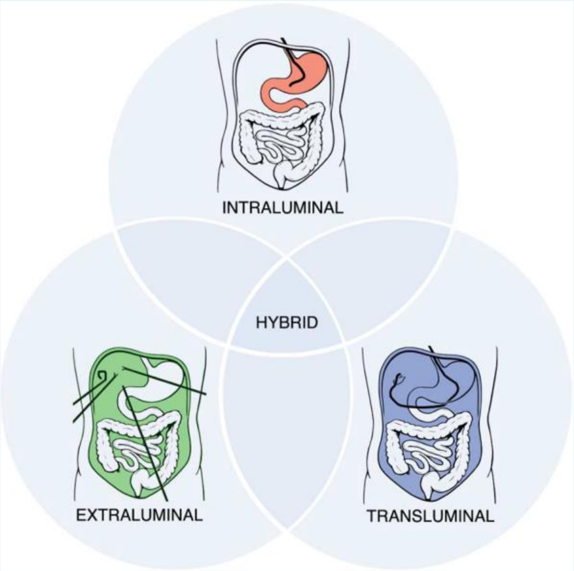

Figure 1 [Ref1]: Classification of minimally invasive surgical procedures based on different access routes to the target operative anatomy, with example abdominal procedures illustrating **extraluminal, intraluminal and transluminal approaches**. The respective operative workspaces are shown in green, red and blue.

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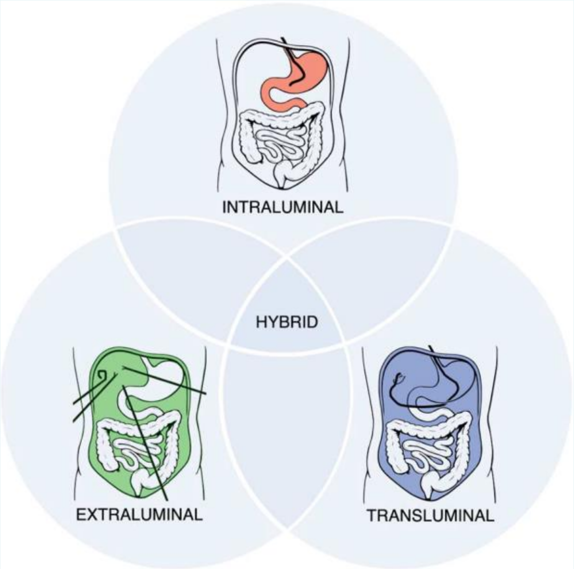
Minimally Invasive (Robotic) Surgery (MIS) Classification (2)

- Extraluminal:
  - Access is usually gained by passage of instruments into a body cavity via >1 small skin incisions (1 needed for camera)
  - Long, straight, rigid instruments
  - 3-12 mm diameter trocar ports.
  - Challenges:
    - Fulcrum point effect
    - Loss of wrist articulation
    - Large operative workspace separating operator hands from instrument tips



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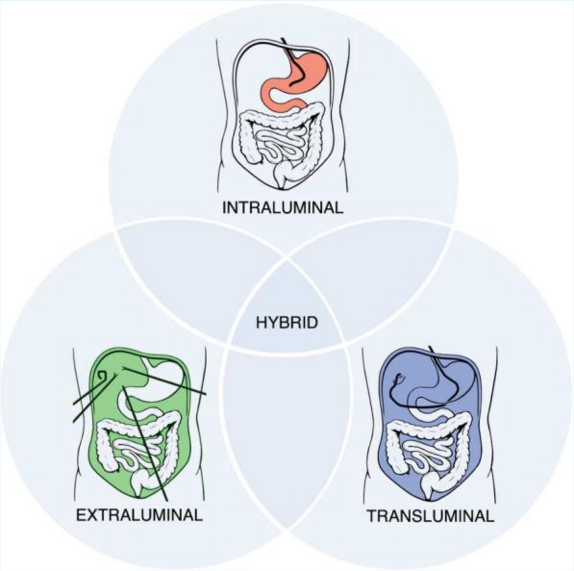
Minimally Invasive (Robotic) Surgery (MIS) Classification (3)

- Transluminal:
  - Access is provided via a controlled breach of a luminal barrier for entry to body cavities such as the abdomen.
  - Challenges:
    - Same as intraluminal, PLUS:
    - Safe closure of luminal access point(s)
    - Stability and force for tool-tissue interaction



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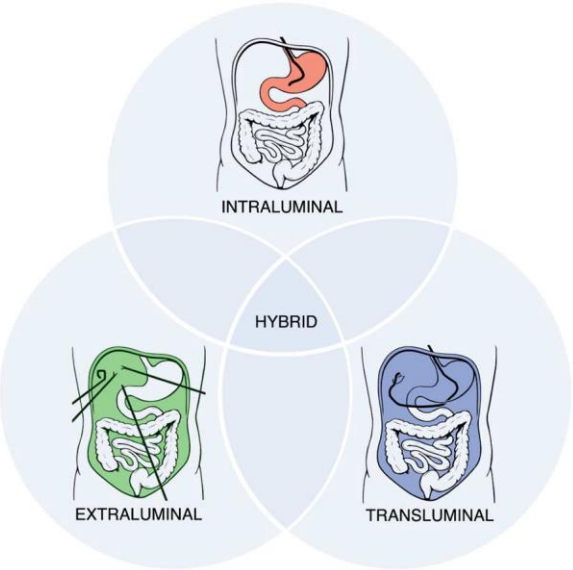
Minimally Invasive (Robotic) Surgery (MIS) Classification (4)

- Hybrid approaches use a combination of these access routes.



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Extraluminal Procedures (1)

- Laparoscopy (abdomen) and thoracoscopy (chest) are examples of minimally invasive techniques that utilize extraluminal access routes to insert instruments via small incisions in the abdominal or chest wall.

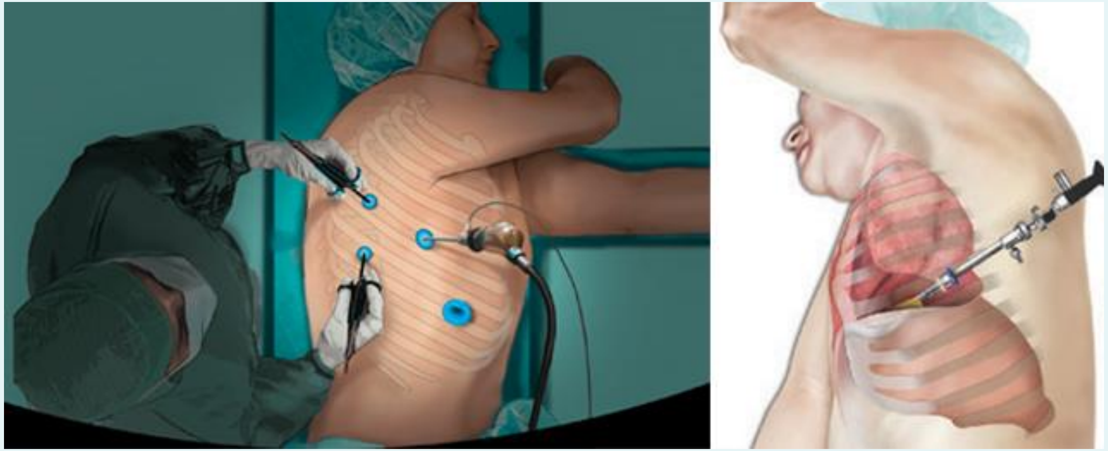


Figure 1: Thoracoscopy procedure with standard tools [Source: https://www.sreedharchestclinic.com/thoracoscopy.html]

Extraluminal Procedures (2)

- Ports anchored at these access sites support long rigid instruments as they are passed inside the body.
- Insufflation of gas in anatomical potential spaces creates and expands a working space for procedures to be undertaken.

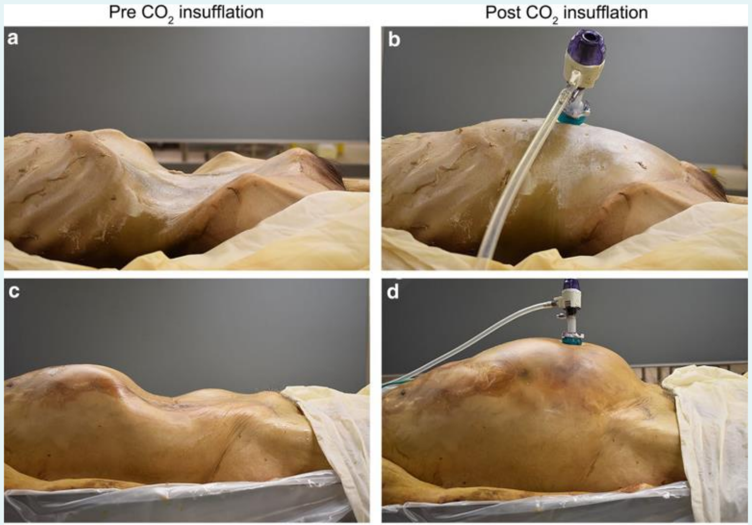


Figure 2: External appearance of the abdomen before (a, c) and after (b, d) CO2 insufflation in the pyrrolidone-embalmed cadavers - this technique ensure improved tissue elasticity allows for realistic inflation) [Ref1].

Ref1: M. Nagase, Y. Kimoto, E. Sunami, and G. Matsumura, “A new human cadaver model for laparoscopic training using N-vinyl-2-pyrrolidone: a feasibility study,” Anat. Sci. Int., vol. 95, no. 1, pp. 156–164, 2020

Extraluminal Procedures (3)

- Ergonomic challenges faced by laparoscopic procedures include:
  - The counterintuitive mirroring of tool movement caused by the fulcrum effect
  - Impaired dexterity due to a loss of wrist articulation through the use of conventional rigid instruments.
  - Since the instrument tip is constrained within a part of a sphere with its origin located at the trocar, the effective workspace is limited.
  - At the same time, the fixed placement and finite number of port sites may constrain the overall workspace that is accessible with a rigid scope and working instruments.

Extraluminal Procedures (4)

- An extensive list of gastrointestinal, hepatopancreatic-biliary, genitourinary and gynecologic procedures are now routinely undertaken laparoscopically or with robotic-assisted laparoscopy [Ref1].

Ref1 - https://www.hcahealthcare.co.uk/about-hca-uk/robotics-and-technology-at-hca/the-da-vinci-surgical-system

Extraluminal Procedures (5)

- Urology
  - Robotic prostatectomy:
    - International gold standard for surgical treatment of prostate cancer showing:
      - Improved cancer outcomes;
      - Less nerve damage in patients post surgery.
    - It is widely accepted as the most effective way to surgically treat urological cancer - 75% performed robotically within the NHS.
  - Robotic nephrectomy for kidney cancer:
    - 77% of partial nephrectomies are performed robotically within the NHS
  - Robotic cystectomy for bladder cancer (removal of a part of the urinary tract)

Extraluminal Procedures (6)

- Gynaecology
  - Robotic hysterectomy (removal of the uterus)
    - Robotic technology has made hysterectomies far safer and less invasive.
    - By using a robotically assisted laparoscopic technique, the surgeon has a greater view which allows them to be much more accurate throughout the procedure.
    - It also reduces the chance of the surgeon having to convert to an open operation in comparison to a standard laparoscopic approach where visibility may be limited.
  - Robotic surgery for the treatment of endometriosis (tissue similar to the lining of the womb starts to grow in other places).

Extraluminal Procedures (7)

- Colorectal
  - Robotic Total Mesorectal Excision (TME) for rectal cancer
  - Robotic colectomy for colon cancer
    - Non-robotic surgical techniques can result in patients requiring a colostomy (removal of a portion of the colon) to ensure the safety of the surgical joins.
    - However, when using the robot, as the surgeon’s view is so much better, fewer patients need a colostomy.
    - This means in many cases there’s less need for a second operation, and they can often avoid living with a stoma (artificial opening in the body to divert urine of faeces out of the body).

Extraluminal Procedures (8)

- Liver and Pancreas
  - Robotic hepatectomy
  - Robotic pancreaticoduodenectomy (also known as a Whipple procedure)

Extraluminal Procedures (9)

- Upper Gastroinstestinal
  - Robotic cholecystectomy (resection of the gallbladder) for gallstones
  - Robotic fundoplication to treat gastro-oesophageal reflux disease (GORD)

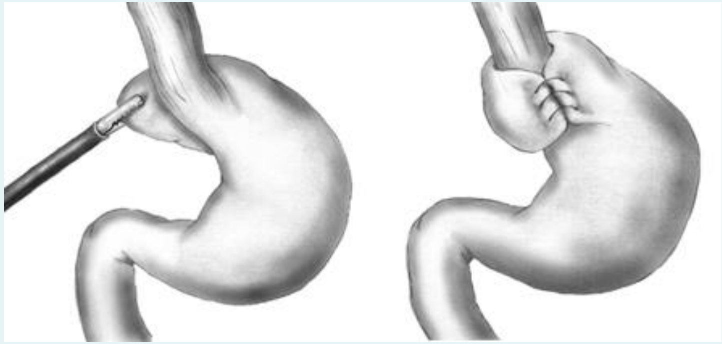


Figure 1: Diagram of a Nissen fundoplication. [Ref1]

Ref1 - By Xopusmagnumx at English Wikipedia. His userpage indicates that he is Dr Gray, the original artist - Transferred from en.wikipedia to Commons by JohnnyMrNinja using CommonsHelper. Watermark removed by JohnnyMrNinja., Public Domain, https://commons.wikimedia.org/w/index.php?curid=10492233

Extraluminal Procedures (10)

- Head, Neck and Thyroid
  - Transoral Robotic Surgery (TORS) for head and neck cancer, or obstructive sleep apnoea and snoring.
    - The dexterity of the robot means surgeons can locate small growths in the mouth and in the throat without having to perform open surgery via the face to expose the neck.
    - This reduces patient trauma significantly without having to risk damage to nerves or vital blood vessels.

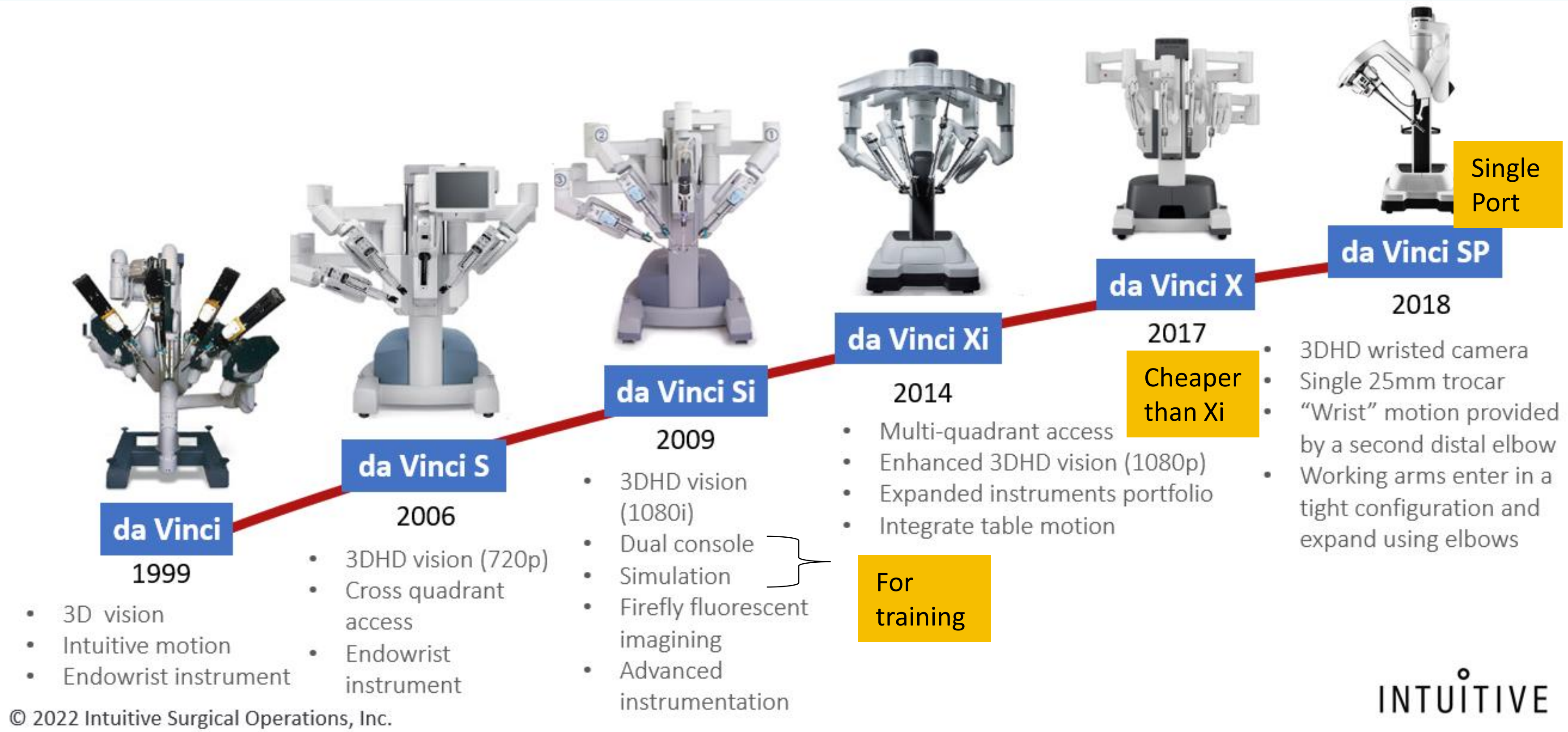
Extraluminal Procedures (11)

- Thoracic
  - Robotic thymectomy for myasthenia gravis or thymus tumours (resection of the thymus gland)
  - Robotic lung surgery for lung cancer
    - Traditionally, thoracic surgery would be performed through a large cut to the chest which can be incredibly uncomfortable.
    - As the chest is always moving, healing and recovery can be challenging – with intense physiotherapy and rehabilitation required.
    - By reducing the size of the cuts through robotic surgery, patients' pain relief is much lower, their rehabilitation needs are reduced and they can return to normal activities more quickly.

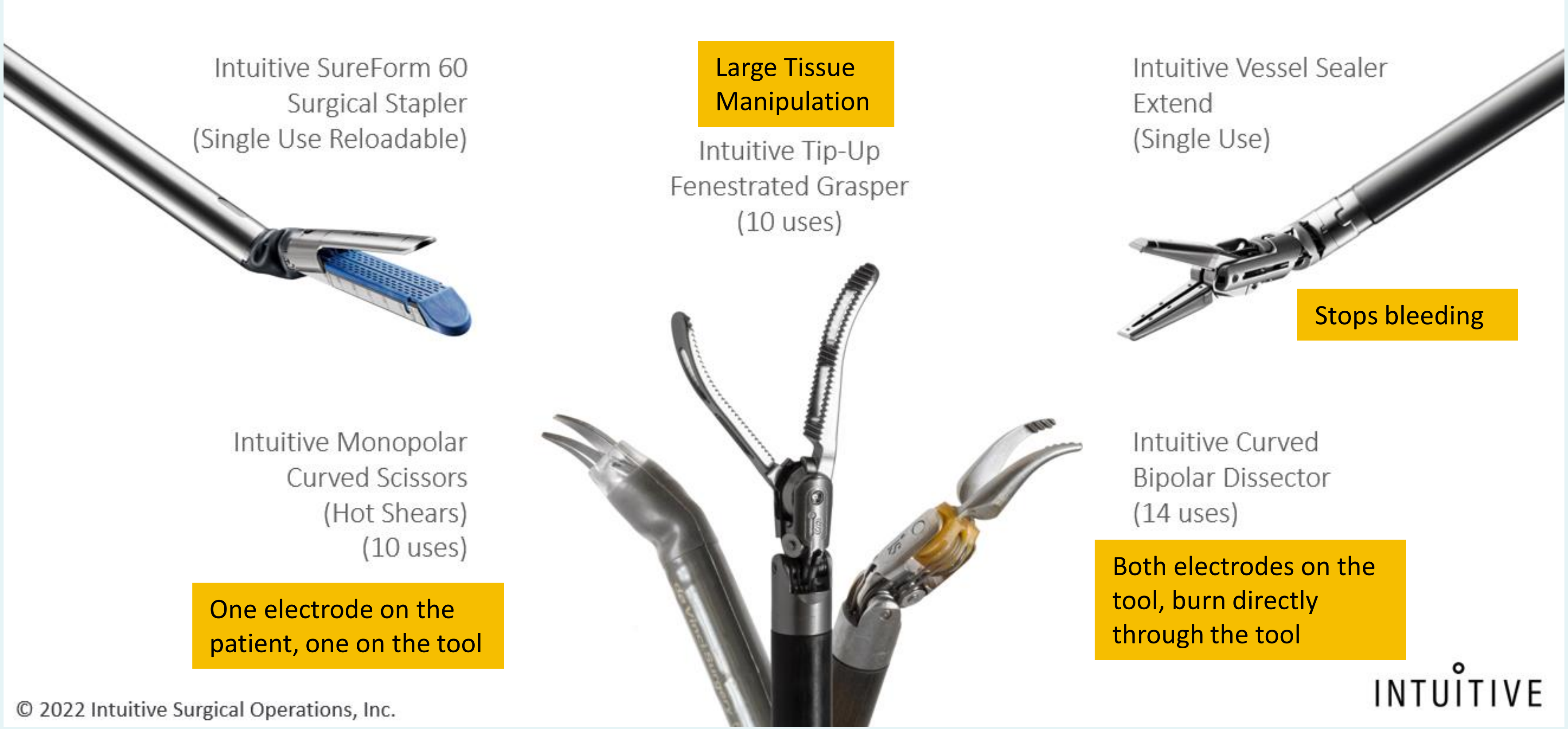
Extraluminal Procedures (12)

- Weight Loss Surgery
  - Robotic gastric sleeve
  - Robotic gastric bypass

Evolution of da Vinci Surgical System



The da Vinci Instruments



Laparo-Endoscopic Single-Site Surgery (1)

- In an attempt to improve cosmesis following laparoscopy, there has been extensive interest recently in techniques to reduce the number of visible skin incisions required for extraluminal instrument access.

  - There are many descriptive titles and acronyms for these emerging single-port surgery techniques. However, a recent consensus statement agreed to use the term Laparo-Endoscopic Single-Site surgery (LESS) [Ref1].

Ref1 - I. S. Gill et al., “Consensus statement of the consortium for laparoendoscopic single-site surgery,” Surg. Endosc., vol. 24, no. 4, pp. 762–768, 2010

Laparo-Endoscopic Single-Site Surgery (2)

- Single port laparoscopy procedures are mostly carried out through the umbilicus using a port that contains multiple smaller internal cannulas through which up to four laparoscopic instruments may be inserted coaxially.
  - da Vinci SP - Single Port – A 2.5 cm cannula controls three fully-wristed, elbowed instruments and the first fully-wristed da Vinci endoscope
    https://www.youtube.com/watch?v=TGjnb86HndU

Ref1 - I. S. Gill et al., "Consensus statement of the consortium for laparoendoscopic single-site surgery," Surg. Endosc., vol. 24, no. 4, pp. 762–768, 2010

Laparo-Endoscopic Single-Site Surgery (3)

- The main drawbacks of single port techniques are:
  - Inadequate triangulation,
  - Instrument crowding,
  - Hands clashing.
- To address these issues, curved instruments with different configurations have been developed.
- However, thus far dexterity has been introduced only at the handle or at the distal tip of the instruments, while the shaft remains rigid.

Ref1 - I. S. Gill et al., "Consensus statement of the consortium for laparoendoscopic single-site surgery," Surg. Endosc., vol. 24, no. 4, pp. 762–768, 2010

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Intraluminal Procedures (1)

- Intraluminal (aka endoluminal) procedures are performed through tubular anatomical structures such as the esophagus, colon, urethra and arteries, without breaching their physiological luminal boundaries.

  - Most of these structures are exposed to the external environment at one of their extremities by natural orifices such as the mouth, anus and external urethral orifice.

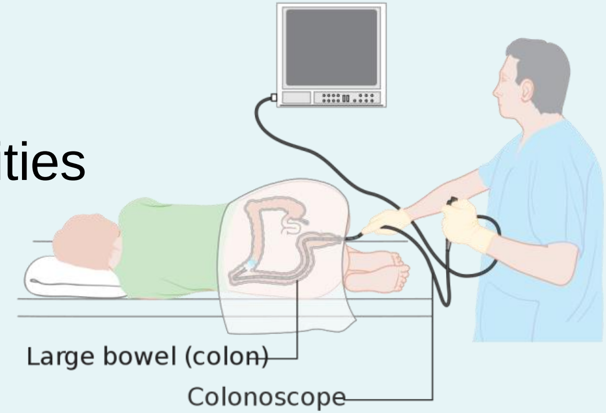

Fig Source Cancer Research UK / Wikimedia Common

Intraluminal Procedures (2)

- Endoscopes can be used to enter via these routes to perform diagnostic procedures (e.g., imaging or biopsy), and therapeutic procedures (e.g., ablation or resection of benign or malignant tissue) [Ref1].
  - E.g. Gastroscopy or duodenoscopy (or generally esophagogastroduodenoscopy (EGD)) is performed for a number of indications, one of the most common being in unexplained anemia, where it is used to diagnose gastric or duodenal ulcers, etc.

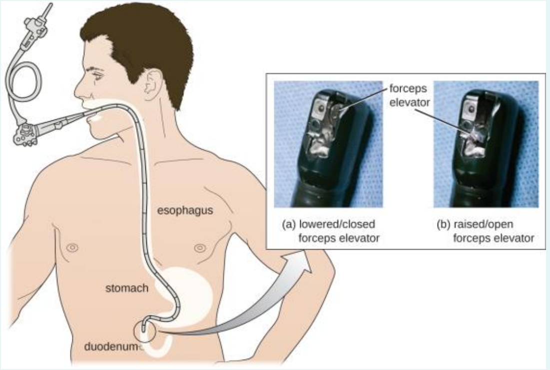

Fig Source CNX OpenStax - https://cnx.org/contents/5CvTdmJL@4.4

Ref1: J. L. Ponsky, “Endoluminal surgery: past, present and future,” Surg. Endosc. Other Interv. Tech., vol. 20, no. 2, pp. S500–S502, 2006.

Intraluminal Procedures (3)

- In contrast to large workspaces usually generated with extraluminal procedures, intraluminal procedures are confined within spatially constrained operative workspaces that define the size and configuration requirements of tools that can be used.

- Due to complex nonlinear luminal boundaries, instrument and tool flexibility is crucial for safe access and navigation.

Intraluminal Procedures (4)

- Intravascular (blood vessels) procedures are a specific case of intraluminal access.
- For intravascular intervention, external imaging such as X-ray fluoroscopy is typically used to guide catheters and place stents and coils and this brings with it a unique set of challenges.

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Transluminal Procedures (1)

- Recently, considerable attention has been focused on further minimizing the invasiveness of the existing MIS approaches, especially for gastrointestinal and hepatobiliary surgery.
  - Among these, transluminal surgery is introduced as an expansion of the intraluminal operations performed by gastroenterologists using flexible endoscopes.
  - These approaches are recognized as Natural Orifice Transluminal Endoscopic Surgery (NOTES), which involves a controlled breach of a luminal barrier to enter body cavities, such as the abdomen.

Transluminal Procedures (2)

- The main benefit here is that any external incision is avoided, so no scars will be visible after the procedure.
- Also, the internal surface of body may have less nerve, therefore less pain.

- Endoscopes may be inserted through a single natural orifice route or a combination of transgastric, transrectal, transvaginal, or transvesical routes for a rendezvous approach.
- Selection of access route is influenced by the specific procedure to be performed and the potential pitfalls associated with each access route [Ref1].

Ref1: D. Rattner and A. Kalloo, "ASGE/SAGES working group on natural orifice translumenal endoscopic surgery," Surg. Endosc. Other Interv. Tech., vol. 20, no. 2, pp. 329–333, 2006..

Transluminal Procedures (3)

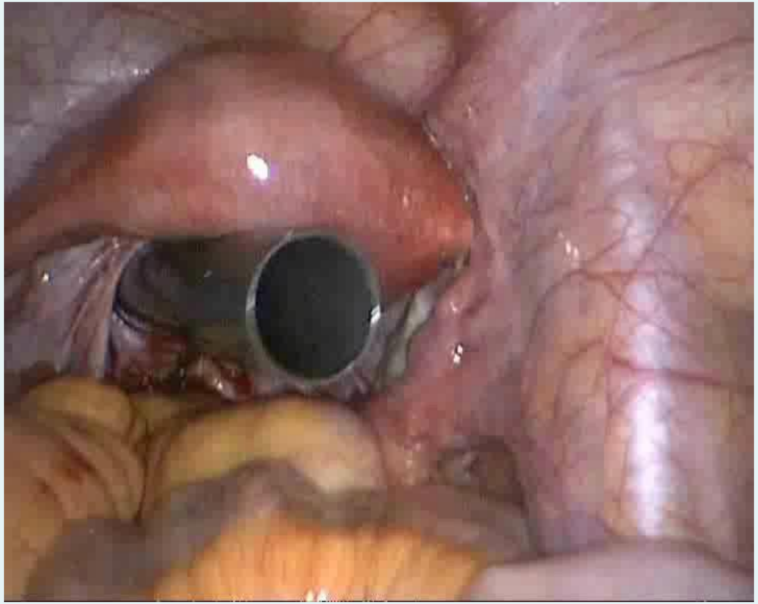

Fig.1: Endoscopic surgery trocar inserted through the vaginal fornix to access the abdominal cavity. The uterus is visible directly above the trocar.

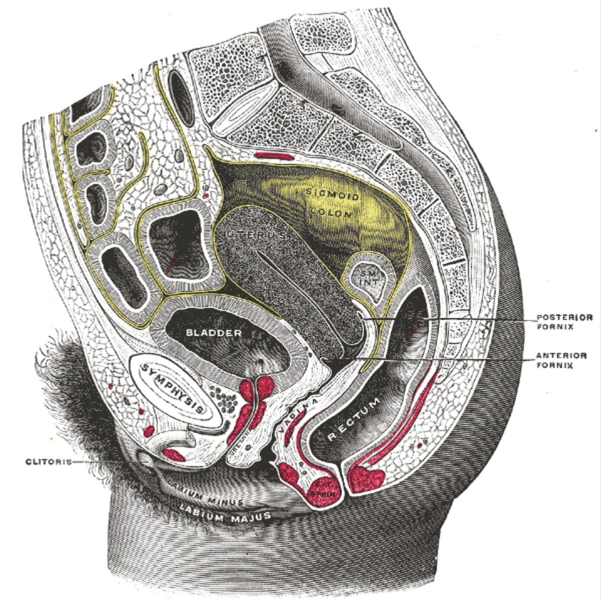

Fig. 2: Sagittal section of the lower part of a female trunk, right segment.

Fig (1) Source: Wikimedia Commons at https://commons.wikimedia.org/wiki/File:Imagennotes.jpg
Fig (2) Source: Wikimedia Commons at https://commons.wikimedia.org/wiki/File:Gray1166.png

Transluminal Procedures (4)

- When compared to intraluminal and extraluminal procedures, transluminal surgery is still predominantly an experimental approach with significantly less commercially available systems specifically designed for this technique.

Transluminal - Challenges (1)

- NOTES holds promise to advance the field of MIS towards even less invasive surgical approaches,

- Unfortunately, the available endoscopic instrumentation is generally inadequate for transluminal procedures.

  - Aside from the mechanically operated distal articulating segment, the flexible endoscope has a passive kinematic design that is often described as “floppy”.

Transluminal - Challenges (2)

- Attempted NOTES applications outside of normally supportive luminal boundaries reveal this lack of structural shape strength by a tendency for the tip to wander away from the desired target.

- Additionally, current surgical tools and devices compatible with flexible endoscopes cannot guarantee the required tissue dissection, destruction and reconstruction capabilities.

- The design of specialized instrumentation is therefore critical to the clinical uptake of NOTES.

Transluminal - Challenges (3)

- The major technical challenges for effective NOTES instrumentation are related to
  - The flexibility of instruments to allow navigation to the operative site through different access routes
  - While maintaining adequate stability and triangulation for tissue manipulation.

- The goal is to meet the same capabilities of complex multi-handed laparoscopic instruments, which in turn seek to reproduce the abilities of human hands to perform open surgery.
  - This is accomplished by a platform design that is anthropomorphically inspired by the features of hands and eyes.

Transluminal - Challenges (4)

- Elevated optics above the operating tools may provide a more unobstructed view of the operative field that is similar to laparoscopic and open surgery.

- Coupled with this, bimanual arms with independent control may deliver intuitive and enhanced capacity for tissue manipulation, including traction and counter-traction.

- The integration of these elements into such a platform design represents a major technical challenge.

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Hybrid Approaches (1)

- Hybrid approaches encompass those procedures that utilize a combination of the access routes used in the three scenarios discussed so far.
  - In the transition towards pure NOTES procedures, there has been a reliance on hybrid approaches that utilize extraluminal deployment of laparoscopic instruments to aid safety and feasibility for procedures involving transluminal access.
  - These hybrid approaches are sometimes described as laparoscopy-assisted NOTES or Mini laparoscopy-Assisted Natural Orifice Surgery (MANOS) [Ref1].

Ref1: M. H. Sodergren, J. Clark, T. Athanasiou, J. Teare, G.-Z. Yang, and A. Darzi, “Natural orifice translumenal endoscopic surgery: critical appraisal of applications in clinical practice,” Surg. Endosc., vol. 23, no. 4, pp. 680–687, 2009.

Hybrid Approaches (2)

- Another hybrid approach involves the use of intravascular techniques during cardiac surgery [Ref1].
  - During these procedures, intraoperative stenting or balloon occlusion is carried out intraluminally concurrently with extraluminal surgical interventions.
  - This permits a strategy to mitigate the invasiveness of cardiac procedures that otherwise might require a large thoracotomy or sternotomy incision.

Ref2: V. E. Hjortdal, A. N. Redington, M. R. De Leval, and V. T. Tsang, “Hybrid approaches to complex congenital cardiac surgery,” Eur. J. cardio-thoracic Surg., vol. 22, no. 6, pp. 885–890, 2002.

Hybrid Approaches (3)

- Another e.g. of hybrid approaches - robotically assisted prostate intervention with strong focus on the delivery of brachytherapy
  - A good review of these systems can be found in [Ref2].

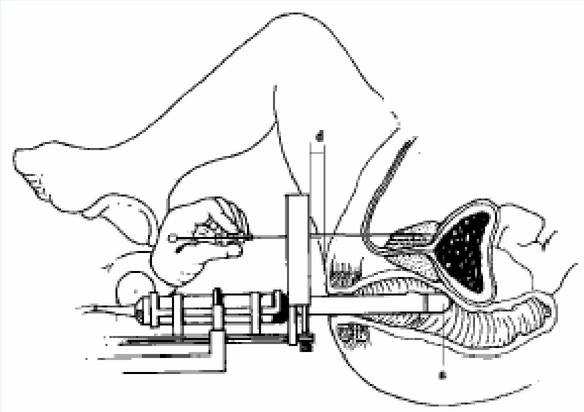

Fig. 1 : Brachytherapy traditional clinical scenario with use of a TransRectal Ultrasound (TRUS) Probe for needle guidance [Ref1].

Ref1: https://www.aapm.org/meetings/amos2/pdf/49-14448-11758-141.pdf

Ref2: P. Kulkarni, S. Sikander, P. Biswas, S. Frawley, and S.-E. Song, “Review of robotic needle guide systems for percutaneous intervention,” Ann. Biomed. Eng., vol. 47, no. 12, pp. 2489–2513, 2019.

Emerging Robotic Platforms And Advanced Instrumentation For MIS (1)

Ref1: V. Vitiello, S.-L. Lee, T. P. Cundy, and G.-Z. Yang, “Emerging robotic platforms for minimally invasive surgery,” IEEE Rev. Biomed. Eng., vol. 6, pp. 111–126, 2012.

Platform	Extraluminal	Intraluminal	Transluminal	Commercially available	Robotic actuation	Tri-angulation	Flexible (F)/ Rigid (R)	Interchangeable instrument channels	Built-in (B)/ Insertable (I) camera	Strengths (+) and weaknesses (-)
Endoscopic platforms										
 Transport (USGI Medical) [19] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	✓	×	✓	F	✓	I	(+) Shape-lock® stiffening endoscopic over-tube technology (-) Poor triangulation, complex control and difficult to achieve smooth and precise tip motion
 Cobra (USGI Medical) [19] (©2009 IEEE. Reprinted, with permission, from [25])	×	×	✓	×	×	✓	F	×	I	(+) Shape-lock® stiffening endoscopic over-tube technology, three independent arms for improved triangulation (-) Large diameter, fixed tools, complex control, difficult to achieve smooth and precise motions
R-Scope (Olympus) [21]	×	✓	✓	✓	×	✓	F	✓	B	(+) Instrument channels with elevators on perpendicular planes (-) Complex controls, disorientation and insufficient force transmission
NeoGuide (NeoGuide Systems Inc) [24]	×	✓	✓	✓	✓	×	F	✓	B	(+) Automatic control of electro-magnetically coupled flexible segments (-) No triangulation
 Anubiscope (Karl Storz/ IRCAD) [26] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	✓	×	✓	F	✓	B	(+) Tulip-shaped distal tip with flaps that open to reveal two triangulating movable arms with working channels for flexible instrument insertion (-) Limited maneuverability in the endoluminal space, complex control and limited triangulation
Incisionless Operating Platform – IOP (USGI Medical) [27]	✓	✓	✓	✓	×	✓	F	✓	I	(+) Ergonomic user interface for simultaneous use of up to three custom-made endoscopic instruments (-) Inability to perform advanced endoluminal procedures
 EndoSamurai (Olympus) [28] (Reprinted from [27], ©2012, with permission from Elsevier)	×	×	✓	✓	×	✓	F	✓	B	(+) Fitted with two bendable hollow arms and laparoscopic interface to enhance bimanual coordination (-) Requires at least two operators and the arms limit manoeuvrability within lumens and during retroflexion
 DDES (Boston Scientific) [29] (Reprinted from [27], ©2012, with permission from Elsevier)	×	✓	×	✓	×	✓	F	✓	I	(+) Mobile rail platform featuring a steerable flexible articulating guide sheath with three channels for the passage of articulated flexible mechanically controlled instruments (5 DoFs) (-) Inaccuracy of tendon-driven motion, limited triangulation and force transmission
SPIDER (TransEnterix, Inc) [30]	✓	×	×	✓	×	✓	F	✓	I	(+) Laparoscopic interface allowing for simultaneous use of two flexible endoscopic instruments and a rigid mini-laparoscopic tool (-) Limited triangulation and force, needs at least two operators
ViaCath (Hansen Medical) [31]	×	✓	✓	×	✓	✓	F	✓	B	(+) Telemanipulation of flexible tools comprising a flexible shaft and articulated tip with end-effector (7 DoFs) (-) Limited triangulation and lateral force
 MASTER [32] (©2009 IEEE. Reprinted, with permission, from [33])	×	×	✓	×	✓	✓	F	✓	B	(+) Slave manipulator attached to the tip of a standard dual-channel endoscope featuring two 4-DoF arms and a gripper (-) Large diameter of the cap, fixed end-effectors, cumbersome actuation pack, needs at least two operators

Emerging Robotic Platforms And Advanced Instrumentation For MIS (2)

Ref1: V. Vitiello, S.-L. Lee, T. P. Cundy, and G.-Z. Yang, “Emerging robotic platforms for minimally invasive surgery,” IEEE Rev. Biomed. Eng., vol. 6, pp. 111–126, 2012.

Platform	Extraluminal	Intraluminal	Transluminal	Commercial-ly available	Robotic actuation	Tri-angulation	Flexible (F)/ Rigid (R)	Interchange-able instrument channels	Built-in (B)/ Insertable (I) camera	Strengths (+) and weaknesses (-)
 Master-slave system for NOTES (IRCAD) [34] (©2009 IEEE. Reprinted, with permission, from [25])	×	✓	✓	×	✓	✓	F	✓	B	(+) Special cap attached to the tip of a standard endoscope featuring two snake-like hollow arms with 2 DoFs; the endoscope motion is also motorized (-) Cumbersome components, limited triangulation and lateral force
HVSPS (Munich Technological University) [35]	✓	×	×	×	✓	✓	F	✓	B	(+) Third arm to place a standard endoscope in an S-shape perpendicularly to the plane of the instruments for enhanced triangulation (-) Large diameter, complex control, needs at least four operators
 Single port system (Waseda University) [36] (©2011 IEEE)	✓	×	×	×	✓	✓	F	×	B	(+) Slave part comprising a positioning RCM manipulator, a rigid insertable tool connected to a flexible end controlling a flexible endoscope and two custom-made endoscopic tools (-) Positioning error, limited workspace and tool interchangeability
TEM Instrument System (Richard Wolf) [37]	×	✓	×	✓	×	×	R	✓	B	(-) Limited workspace, rigid instruments, no triangulation
TEO® - Transanal Endoscopic Operation (Karl Storz) [38]	×	✓	×	✓	×	×	R	✓	B	(-) Limited workspace, rigid instruments, no triangulation
Articulated robots										
 HARP (Carnegie Mellon University) [39] (©2012 John Wiley and Sons. Reprinted, with permission, from [40])	✓	×	✓	×	✓	✓	F	✓	I	(+) High flexibility, follow-the-leader locomotion, two lateral flexible arms (-) Limited radius of curvature, large size of feeder, limited triangulation
 i-Snake® (Imperial College London) [41, 42]	✓	×	✓	×	✓	✓	F	✓	I	(+) Modular joint unit based on a hybrid micromotor/tendon design allowing independent control of each rotational DoF while leaving sufficient space for internal channels within the links (-) Limited lateral force of the flexible arms when configured in bimanual mode
 IREP (Vanderbilt University) [43] (©2012 IEEE)	✓	×	×	×	✓	✓	F	×	B	(+) Can be folded into a 15mm diameter configuration for deployment through a standard trocar port, features two 6-DoF arms and 3D camera with 3 DoFs (-) No *in vivo* tests reported, limited dexterity for suturing, slow motions and cumbersome actuation pack
 SPRINT (Scuola Superiore Sant'Anna) [44] (©2012 IEEE. Reprinted, with permission, from [45])	✓	×	×	×	✓	✓	R	×	B	(+) Features two 6-DoFs arms that can be passed in turn through a standard 30mm trocar port and a stereoscopic camera (-) Complex assembling, need for specialised trocar, large size and limited workspace
 Miniature robots (University of Nebraska Medical Center) [46] (Reprinted from [47] , ©2009, with permission from Elsevier)	✓	✓	✓	×	✓	✓	R	×	B	(+) Completely insertable miniature camera and dexterous robots (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission
Miniature robots (University of Texas Southwestern Medical Center) [48]	✓	✓	✓	×	✓	×	R	×	B	(+) Completely insertable multi-DoF cameras and manipulators (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission
 Endoluminal Robotic Platform (Scuola Superiore Sant'Anna) [49] (©2012 IEEE)	×	✓	×	×	✓	×	R	×	B	(+) Reconfigurable robotic modules (anchoring devices, cameras and manipulators) that can be inserted endoluminally (-) Complex set-up for magnetic anchoring and guidance in the operative room, use of wires for power and image transmission

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Intraluminal – Colorectal Cancer (1)

- Colorectal cancer (CRC) is the second leading cause of cancer death in both sexes, accounting for 10 to 11 percent of cancer deaths overall;
  - It is third most common in men and women separately.
  - Approximately one in three people who develop CRC die of this disease.

- Nonetheless, almost 60% of CRC deaths could be prevented with screening.

Intraluminal – Colorectal Cancer (2)

- Colonoscopy remains the prime mean of screening for CRC.
  - However, colonoscopy attendance rates are affected by discomfort, fear of pain and embarrassment or loss of control during the procedure.

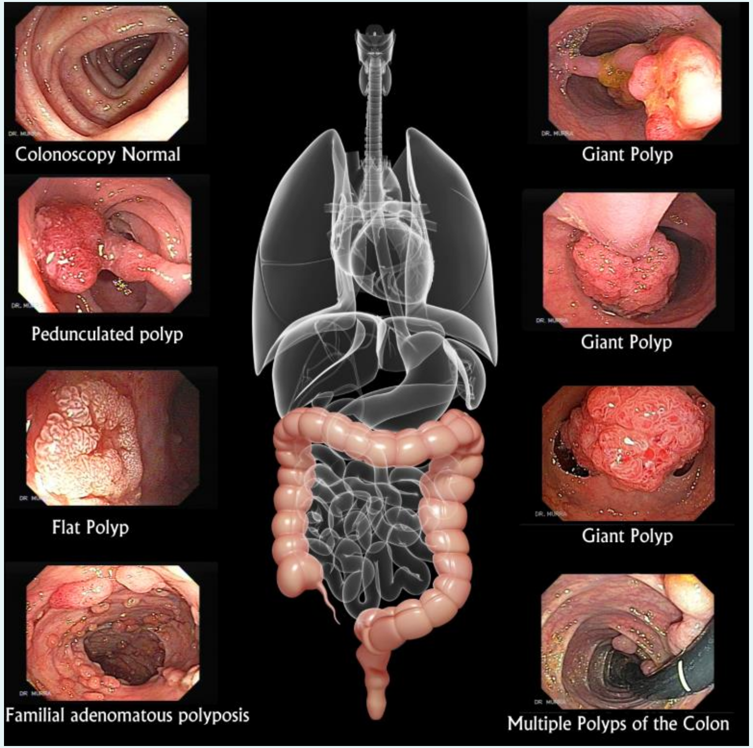
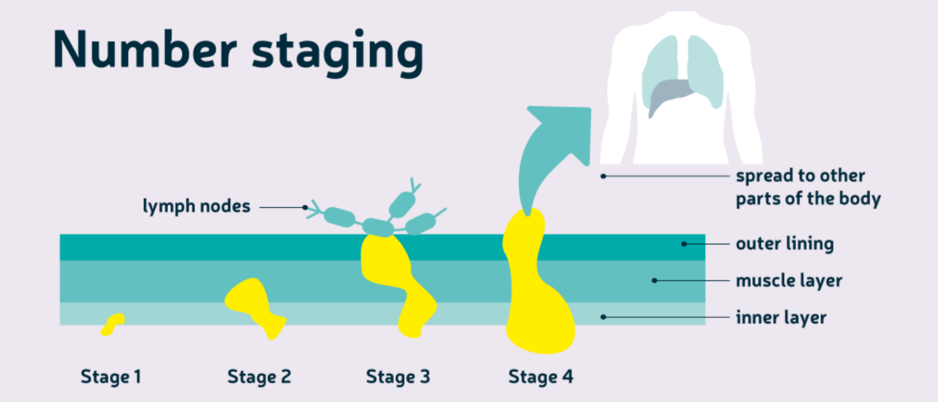
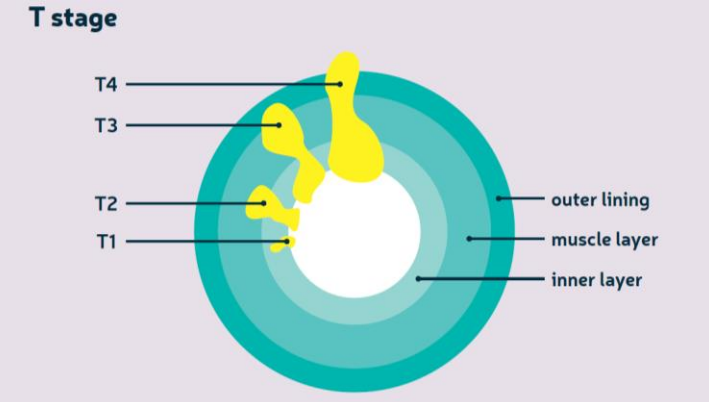


Fig.1: Healthy colon and colon affected by different types of polyps (pre-cancerous formations).

Fig.1: Source: https://www.murrasaca.com/english/colon-cancer.html

Intraluminal – CRC Stages (1)





- 5-Years Survival Rate
  - Stage I – More than 95 %
  - Stage II – 70 %
  - Stage III – 50 %
  - Stage IV – Less than 5

Figures source: https://www.bowelcanceruk.org.uk/about-bowel-cancer/diagnosis/staging-and-grading/

Intraluminal – CRC Stages (2)

- Stage specific treatment:

- Stage I and II:
  - The common treatments are intraluminal surgery and chemotherapy (not always needed)
  - For more spread cancers minimally invasive extraluminal surgery may be needed.

Intraluminal – CRC Stages (3)

- Stage III:
  - Surgery is typically performed using minimally invasive extraluminal approaches (when possible) to remove the cancer cells
  - Always combined with chemotherapy and radiotherapy.
  - With stage III a colostomy procedure is performed to remove a portion, or the totality, of the colon and a temporary or permanent stoma will be placed on the surface of the abdomen.

Intraluminal – CRC Stages (4)

- Stage IV:
  - Open or minimally invasive surgery is typically not effective as a form of treatment, even when combined with chemotherapy and radiotherapy.
  - It can be performed to improve the quality of life.
  - Survival rate at this stage is very low.

Intraluminal – Robotic Colonoscopy (1)

- The translation of robotic technologies from traditional surgery to minimally invasive endoscopic interventions is an emerging field, mainly challenged by the tough requirements for miniaturization.
  - Pioneering approaches for robotic colonoscopy have been reported in the 90s, with the appearance of inchworm-like devices.
  - Since then, robotic colonoscopes with assistive functionalities have become commercially available.

Intraluminal – Robotic Colonoscopy (2)

- Research prototypes promise enhanced accessibility and flexibility for future therapeutic interventions, even via autonomous or robotic-assisted agents, such as robotic capsules.
- Furthermore, the pairing of such endoscopic systems with AI-enabled image analysis and recognition methods promises enhanced diagnostic yield.

Intraluminal – Robotic Colonoscopy (3)

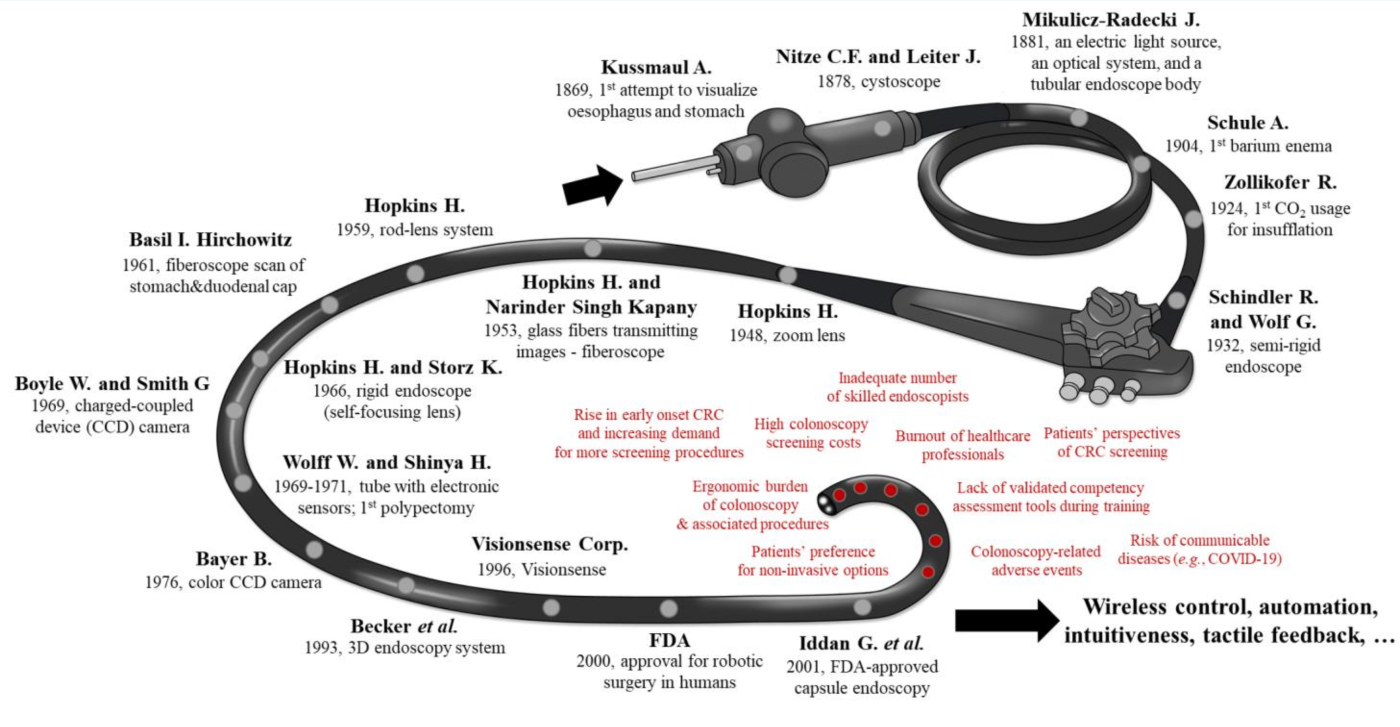


Fig. 1: Graphical representation of all the key milestones in colonoscopy (black text) and possible factors impeding future high-throughput colonoscopy screening programs (red text).

Fig.1: Source: G. Ciuti et al., "Frontiers of robotic colonoscopy: a comprehensive review of robotic colonoscopes and technologies," J. Clin. Med., vol. 9, no. 6, p. 1648, 2020.

Non-robotic colonoscopes and colonoscopy adjuncts (1)

- Available in the clinical practice.

Device	Distinctive Features	Advantages	Limitations
Standard Colonoscopy (SC)	Long semirigid instrument (~13 mm in diameter and ~1400 mm in length) with a 2-DoFs cable-driven steerable tip, manually introduced through the anus and pushed forward and backward to inspect the colonic wall (+ 1-DoF axial-roll).	Current reference standard for diagnosis and treatment; diagnosis and treatment in the same session; manual fine control of the endoscope tip.	Requires unpleasant laxative preparation, sedatives, and analgesia; uncomfortable procedure due to insufflation and tissue-colonoscope interaction; highly dependent of endoscopist training and ability; looping and potential risk of perforation (0.1–0.3% for diagnostic colonoscopies).

Non-robotic colonoscopes and colonoscopy adjuncts (2)

- Available in the clinical practice.

Device	Distinctive Features	Advantages	Limitations
Virtual Colonoscopy Computed Tomography (CCT)	Medical imaging diagnostic procedure using x-rays to compute 3D reconstructed endoluminal views of the colon.	Alternative to conventional colonoscopy to diagnose disease, e.g., polyps and diverticulosis, without discomfort generally caused by colonoscope-lumen interaction.	Requires unpleasant laxative preparation; only CT-based morphological tissue analysis; uncomfortable procedure due to insufflation; sedatives, and analgesia often required; no tissue treatment or surgery; PDR limited (30% of the polyps are flat and obscured).

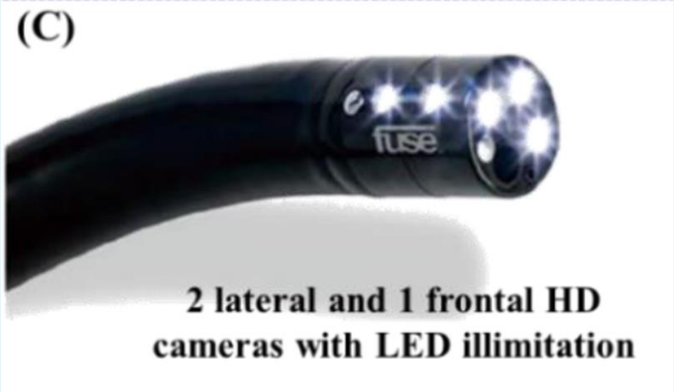
Non-robotic colonoscopes and colonoscopy adjuncts (3)

- Available in the clinical practice.

Device	Distinctive Features	Advantages	Limitations
Double-Balloon Colonoscopy (DBC)	About 2 m long system including a high-resolution endoscope and two latex balloons filled with air by using pressure pumps for easing navigation.	Relatively shorter time of colon examination, and reduced conscious sedation if compared to SC; used in the cases of technical difficulties, e.g., loop formation, long colonic segments, or suspected adhesions, resulting in the discovery of advanced neoplasia, colon polyps, stenosis and Crohn's disease, that were not identified with SC.	Same of SC (often, with reduced discomfort, looping and risk of tissue damage); lack of fluoroscopic evaluation.

Non-robotic colonoscopes and colonoscopy adjuncts (4)

- Available in the clinical practice.



Device	Distinctive Features	Advantages	Limitations
Full Spectrum Endoscopy (FUSE) (EndoChoice Inc., Alpharetta, GA, USA)	Flexible colonoscope with extra optics (i.e., three 4K Ultra HD cameras), allowing to view the gut with a panoramic 330° FoV (behind and into folds).	Maintaining standard features and functions of SC (e.g., 3.8mm working channel), FUSE demonstrated a higher lesions detection rate (mainly in the right and middle parts of the colon), compared with SC (missing rate 7% vs. 41%).	Equivalent to SC; trials failed to replicate higher performances if compared to forward-viewing approach colonoscopy in ascending colon; lower APC than SC (1.30 ± 1.96 vs. 1.53 ± 2.33).

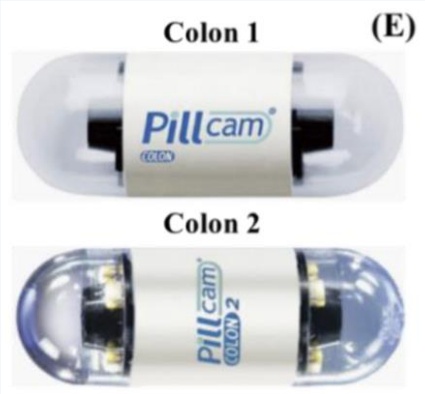
Non-robotic colonoscopes and colonoscopy adjuncts (5)

- Available in the clinical practice.

Device	Distinctive Features	Advantages	Limitations
G-Eye Endoscope (NaviAid G-EYE, SMART Medical Systems Ltd., Ra'anana, Israel)	Flexible colonoscope with an integrated inflatable balloon at its distal portion.	Balloon inflation allows, during withdrawal: (1) straightening and flattening of haustral folds, (2) inhibiting slippage of the bowel, and (3) instrument stabilization and centralized optics; higher ADR and PDR, including well-formed, flat, and sessile serrated ones, if compared to SC.	Equivalent to SC due to the same forward procedure.

Non-robotic colonoscopes and colonoscopy adjuncts (6)

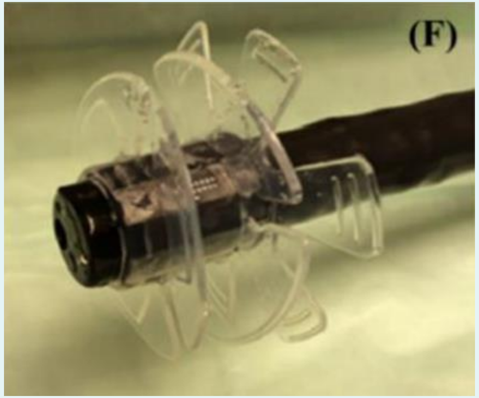
- Available in the clinical practice.



Device	Distinctive Features	Advantages	Limitations
Wireless Capsule Endoscopes (PillCam™ Colon 2) (Medtronic Inc., Minneapolis, Minnesota, USA)	Pill-size wireless screening tools (~11 mm in diameter and ~32 mm in length) with a sub-VGA, adaptive 4 to 35 fps, 172° FoV, and ~0–30mm DoF frontal/rear CMOS double cameras with synchronized activated LEDs.	Minimally-invasive and painless; high-patient tolerability; negligible risk of perforation.	Requires unpleasant and aggressive laxatives preparation; low-accuracy and reliability for diagnosis; inability to control the capsule; inability to perform therapy and treatment.

Non-robotic colonoscopes and colonoscopy adjuncts (7)

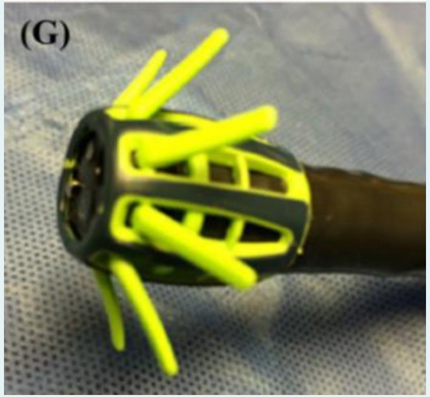
- Available in the clinical practice.



Device	Distinctive Features	Advantages	Limitations
EndoRings™ (adjunct) (EndoAid Ltd., Caesarea, Israel)	Two layers of flexible, soft circular rings - gently flattening folds during withdrawal for a clear view.	Improved visibility, scope centring and control of the endoscope during withdrawal and tissue resection; elevate the ADR in comparison with the FUSE.	Not recommended in cases of acute, severe colitis or of known colonic strictures; performance subject to training and experience.

Non-robotic colonoscopes and colonoscopy adjuncts (8)

- Available in the clinical practice.



Device	Distinctive Features	Advantages	Limitations
Endocuff VISION™ (adjunct) (Olympus Corp., Tokyo, Japan)	Disposable add-on, using arms instead of flaps, to straighten out the mucosa.	Increased ADR if compared to SC, i.e., 35.4% vs. 20.7%, with comparable overall procedure time and without major adverse events. Higher APC than EndoRings™ (1.82 ± 2.58 vs. 1.55 ± 2.42).	Not recommended in cases of acute, severe colitis or of known colonic strictures; performance subject to training and experience.

Non-robotic colonoscopes and colonoscopy adjuncts (9)

Device	Distinctive Features	Advantages	Limitations
Transparent Cap (adjunct) (Reveal® Distal Attachment Cap, Steris Corp., Mentor, Ohio, USA)	Transparent distal attachment, connected to the colonoscope's tip and designed to elevate the ADR via mucosal folds flattening and minimizing a red-out, while preventing the mucosa to adhere to the lens.	Doubtful improvement of ADR, CIR and CIT; a study reports a higher ADR of almost 20% and improved CIR and CIT.	Performance subject to training and experience.

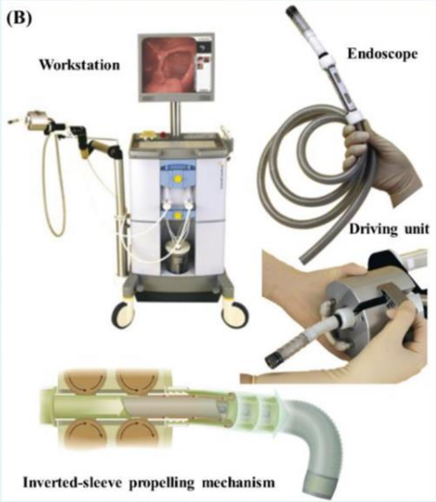
Certified Robotic Colonoscopes (1)

- Commercially-available or no longer on the market.

Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and Clinical Outcomes
NeoGuide Endoscopy System (NeoGuide Endoscopy System Inc., Los Gatos, CA USA)	Electro-mechanical actuation with a "follow-the-leader" mechanism.	16-segment insertion tube that controls the snake-like movement of the endoscope; each independent and electromechanically-controlled segment has 2-DoFs; position sensors at the distal tip of the endoscope and at the external base of the device to obtain live view of the position of the scope's tip, insertion depth and computed real-time 3D mapping of the colon.	Computerized mapping enables the insertion tube to change the segments shape at different insertion depths to reduce looping and unintentional lateral forces and, consequently, patient discomfort; successful and safe (reduction in the looping rate) cecal intubation in 10 patients, with a CIT (with therapeutic invention) of 34 min (range: 24–60 min); FDA obtained in 2006, and acquisition by Intuitive Surgical Inc. in 2009; no longer available on the market and technology translated to Ion, a robotic-assisted endoluminal platform for minimally invasive peripheral lung biopsy.

Certified Robotic Colonoscopes (2)

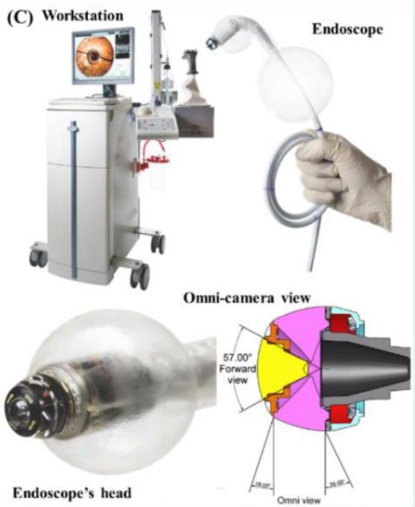
- Commercially-available or no longer on the market.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and Clinical Outcomes
Invendoscope™ SC40 (Invendo Medical GmbH, Weinheim, Germany), then (AMBU A/S, Copenhagen, Denmark)	Electro-mechanical actuation with an inverted sleeve mechanism.	Computer-assisted single-use colonoscope propelled, forward or backward, by an inverted-sleeve mechanism composed of eight drive wheels; robotically-driven tip with LEDs and a CMOS 114° camera, electro-hydraulically flexed through a hand-held control unit to 180° in any direction with full retroflection; diameter of 18 mm and working length of 2000 mm with standard functions including: (1) suction, (2) irrigation, and (3) insufflation with a 3.2 mm working channel, also used for conventional therapeutic procedures.	CIR of 98.4% (median time: 15 min), without any pain, in 92% of patients. 27 polypectomies successfully performed in 23 patients; Invendoscope™ SC40 replaced by a manually inserted single use device with standard flexibility and a hand-held electrical control interface, namely the Invendoscope™ SC200 (as part of the Invendoscopy™ E200 system); latter, obtained the CE mark in 2016 and in January 2018 the FDA clearance for the Invendoscopy™ system E210 and for the Invendoscope™ SC210; no longer available on the market, acquisition by Ambu A/S in 2017.

Certified Robotic Colonoscopes (3)

- Commercially-available or no longer on the market.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and Clinical Outcomes
Aer-O-Scope System (GI View Ltd., Ramat Gan, Israel)	Electro-pneumatic actuation.	Self-propelling, self-steering and disposable robotic colonoscope with navigation obtained through two sealed inflatable balloons and internal pneumatic pressure (inflation of CO_2) for pushing the frontal mobile balloon forward and backward; hand-held control unit to teleoperate the colonoscope's tip with: (1) a 360° omni-directional HD vision system with a 57° FoV camera, (2) LEDs, and (3) two working channels for conventional therapeutic procedures in the latest version; monitored pressure, through electronic sensors, ≤60 mbar.	In-vivo study with 58 patients proved a CIR of 98.2% and a PDR (including all polyps larger than 5mm) of 87.5% compared with SC, and no mucosal damage or adverse events were reported; FDA mark obtained in 2014 (and CE mark in Europe); currently available on the market.

Certified Robotic Colonoscopes (4)

- Commercially-available or no longer on the market.

Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and Clinical Outcomes
ColonoSight (Stryker GI Ltd., Haifa, Israel)	Electro-pneumatic actuation.	Self-advancing system composed of: (1) a reusable colonoscope (EndoSight), with LEDs and a camera, covered by (2) a wrapped disposable multi-lumen sheath with working channel (ColonoSleeve), to prevent infection and eliminate the need for disinfection; powered by an electro-pneumatic unit that insufflates the outer sheath to generate, by progressively unfolding it, a forward force at the distal tip enabling to pull the colonoscope.	Electro-pneumatic mechanism helps reducing the overall "pushing" force; multicentre trial with 178 participants showed a 90% CIR in a mean time of 11.2 ± 6.5 min; biopsies taken in some of the procedures and no complications, e.g., bleeding or perforation, noted, thus showing promising potential over SC; FDA achieved in 2008, no longer available on the market.

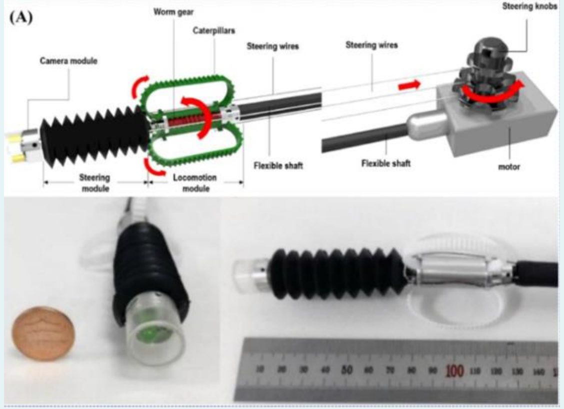
Certified Robotic Colonoscopes (5)

- Commercially-available or no longer on the market.

Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and Clinical Outcomes
Endotics System (ERA Endoscopy Srl, Pisa, Italy)	Electro-pneumatic actuation.	Remotely-controlled (by a hand-held control unit) disposable colonoscope able to semi-autonomously crawl the colon by using two mucosal clamping modules, located at the proximal and distal ends of the probe, and a soft extension/retraction central mechanism, mimicking an inchworm-like locomotion; steerable head, able of a 180° bending angle and, containing: (1) LEDs, (2) a CMOS camera with a 140° FoV, (3) a water and air channel for cleaning/drying the lens and for insufflation, and (4) a 3 mm working channel for conventional therapeutic procedures.	A single-centre prospective pilot study was recently performed with 56 consecutive outpatients (two consecutive blocks of 27—group A—and 28—group B—procedures); CIR was 92.7%, reaching 100% in group B; comparing the two groups, CIT significantly decreased from 55 to 22 min, whereas procedures with CIT < 20 min increased; PDR was 40% (males 62.5%, females 14.3%) and ADR was 26.7% (males 27.5%, females 14.3%); most of patients judged it as mild or no distress, with high willingness to repeat the robotic procedure (92.7%); system available on the market with CE mark obtained in 2011.

Research Robotic Colonoscopes (1)

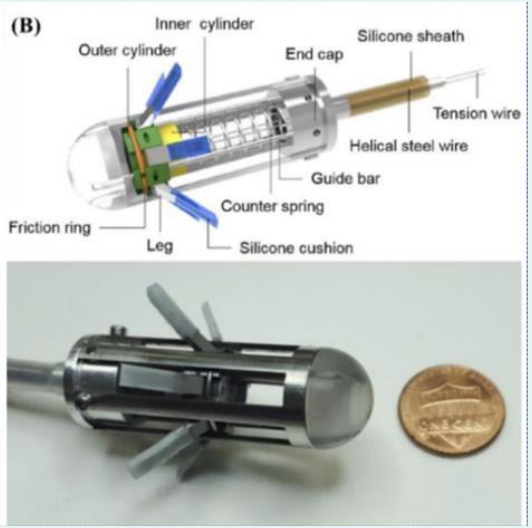
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Kim et al. 2014, Lee et al. 2016 Flexible caterpillar-based robotic colonoscope	Electric actuation.	Flexible caterpillar-based robotic colonoscope, actuated by an external electric motor through a flexible shaft, embedding a steering module (max. bending angle of 178° and min. curvature of the radius of 20mm).	Reliable locomotion in ex-vivo straight excised porcine colon with forward and backward velocities of 5.0 ± 0.4 mm/s and 9.5 ± 0.9 mm/s, respectively (forward velocities of 6.1 ± 1.1 mm/s and 4.7 ± 0.7 mm/s in case of 30° and 60° inclination angles, respectively); ex-vivo tests, performed in a 1 m long excised porcine colon, arranged to mimic human anatomy, revealed a velocity of 3.0 ± 0.2 mm/s with a CIR of 50% and a CIT of 8.55 min, in case of a novice operator (#8 experiments performed); in-vivo tests, performed in a live mini pig, demonstrated the capability to reach the distal transverse colon, 600 mm from the anus, but in-vivo cecal intubation failed due to the mucosa structure and faecal materials.

Research Robotic Colonoscopes (2)

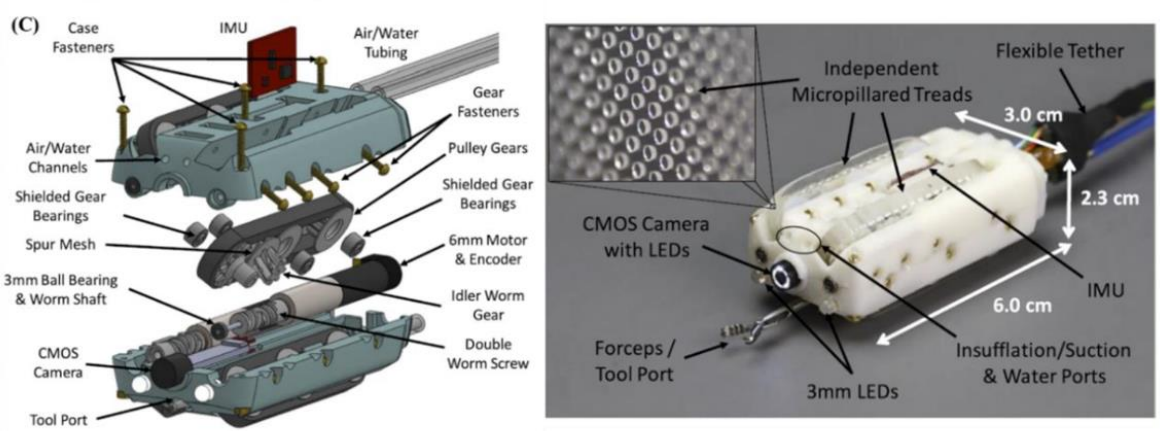
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Lee et al. 2018 and 2019 Reel mechanism-based tethered colonoscope	Electric actuation.	Legged robotic colonoscope based on simple and reliable reel-based mechanism, actuated by an external electric motor.	High manoeuvrability of the colonoscopic device improved, in terms of safety, by harnessing a soft material for the six legs; ex-vivo tests in excised porcine colon demonstrated a 9.552 ± 1.940 mm/s velocity on a flat path, without any scratches or perforations in the porcine tissue.

Research Robotic Colonoscopes (3)

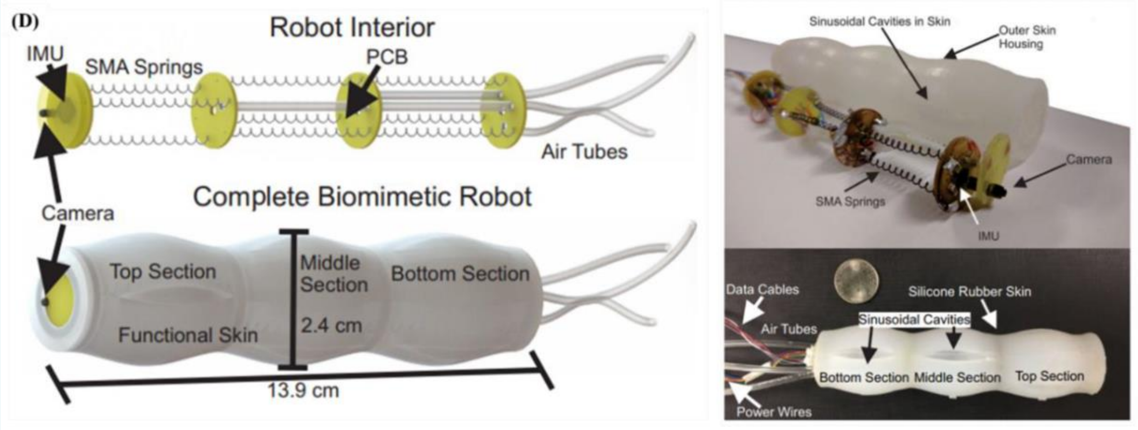
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Formosa et al. 2019 Multi-DOFs sensor-enabled treaded robotic colonoscope	Electric actuation.	Two independently-controlled motors drive micro-pillared treads, above and below the device, for 2-DoFs skid-steering, even in a collapsed lumen; all the functionalities of a SC, i.e., (1) camera, (2) adjustable LEDs, (3) channels for insufflation and irrigation and (4) a tool port for conventional therapeutic procedures; in addition, it embeds (5) an inertial measurement unit, magnetometer, motor encoders, and motor current sensors for potential autonomous navigation.	In-vivo preliminary test in a live pig showed endoscopic functionalities and promising results in terms of locomotion (even if it was not able to gain consistent traction in the sigmoid area, seemingly due to excessive constriction upon the non-treaded sides of the devices); ex-vivo tests demonstrated forward/reverse locomotion up to 40 mm/s on the colon mucosa (both not insufflated and distended), 2-DoFs steering, and the ability to traverse haustral folds, and functionality of endoscopic tools.

Research Robotic Colonoscopes (4)

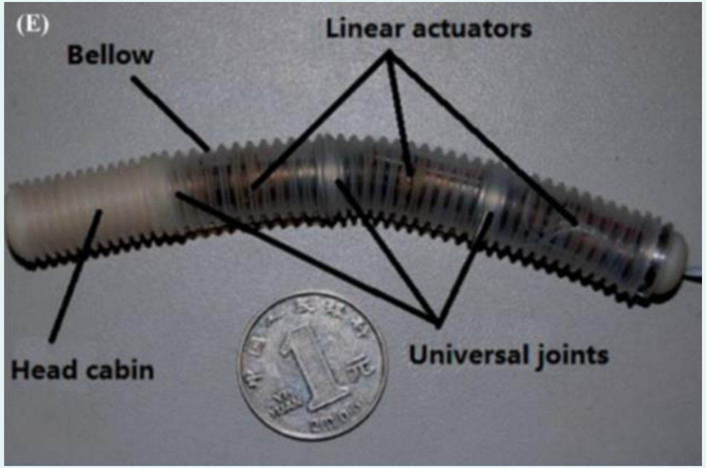
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Ortega et al. 2017 SMA-based three modular section soft robotic colonoscope	Electric actuation.	Each module is featured by 3-DoFs (one translation, using a peristaltic motion to translate, and two rotations); nine independently controlled SMA springs as actuators and a silicone rubber skin to passively recover force to expand the springs to the original state; three air tubes, one for each section, to provide forced convection for cooling SMA springs; orientation between −90° and +90° in both pitch and roll in less than 4 s with near zero steady state error.	In-vitro tests (rigid tube and open environment) demonstrated a peristaltic motion with a maximum and average speed of 4 mm/s and 0.36 mm/s, respectively.

Research Robotic Colonoscopes (5)

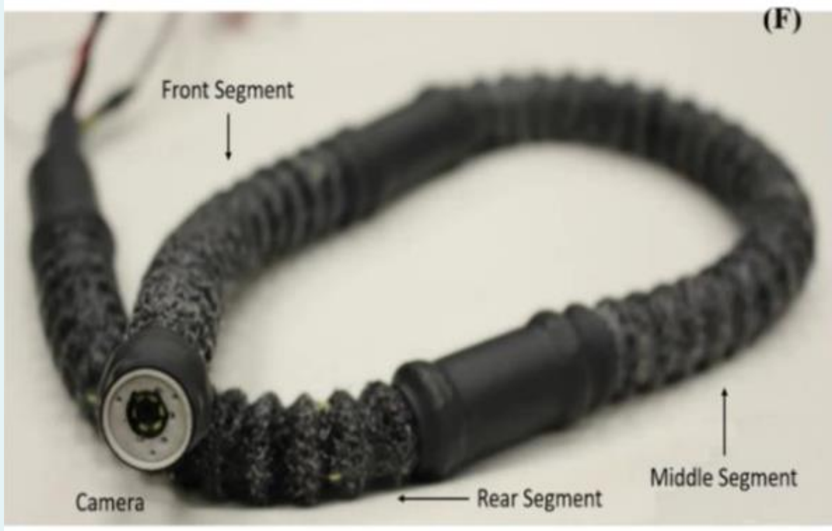
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Wang et al. 2017 Worm-like lightweight robotic colonoscope	Electric actuation.	Lightweight robot (13 mm diameter, 105 mm in length and 22.3 g in weight) with three independent segments, each one composed of a linear locomotor with micromotor, turbine-worm and wire wrapping-sliding mechanism; covered by an external soft bellow with excellent compatibility, designed to increase the static friction and decrease the kinetic friction in the contact state.	In-vivo tests in a porcine model, demonstrating an excellent locomotion capability and safety in soft tissues, with a speed ranging between 1.62 and 2.20 mm/s and passing the entire colon with a CIT of 119s.

Research Robotic Colonoscopes (6)

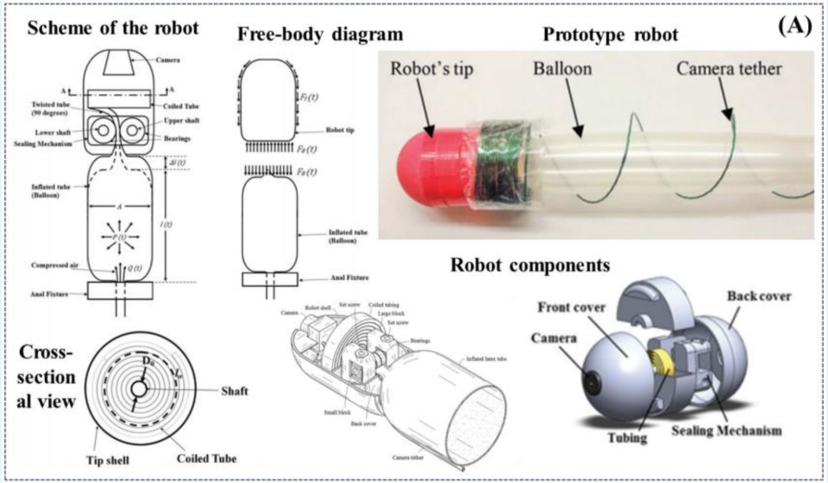
- Electric Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Bernth et al. 2017 Cable-driven actuated worm-like robotic colonoscope	Electric actuation.	Worm-like endoscopic robot, based on an embedded electrical cable-driven actuation system; composed of three segments: the two distal segments bend, allowing steering, while the middle segment extends and contracts along the axial direction for forward and backward locomotion.	Efficient navigation through sharp bending radius curves and proper anchoring in complicated 3D and narrow colonic deformable environments; locomotion strategy avoids high pushing forces associated with SC; fabricated with soft material thus, compliant and flexible for gently passing through irregular and curved sections (potential reduced pain for patients).

Research Robotic Colonoscopes (7)

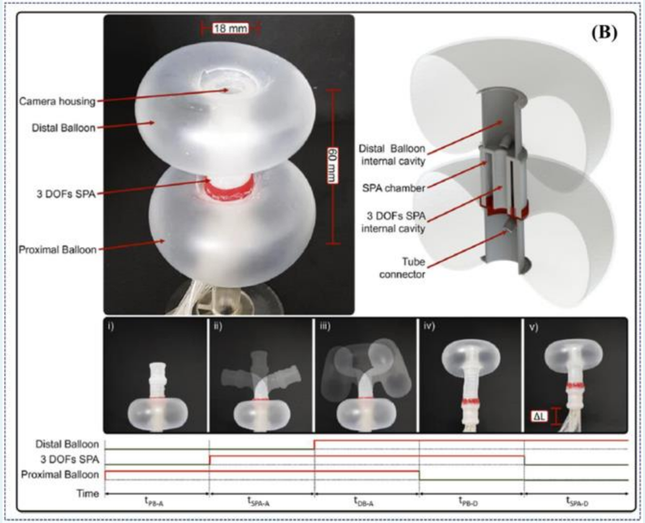
- Pneumatic Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Dehghani et al. 2017 Semiautonomous pneumatically-driven robotic colonoscope	Pneumatic actuation.	Propulsion taking advantage of a longitudinal expansion of an internal latex tube; lightweight and low inertia colonoscopic robot.	Preliminary ex-vivo tests, in excised porcine colon, demonstrated inherently prevention of loop formation (i.e., general cause of pain); successful advancement of 1500 mm, average speed of 28 mm/s and capability of traversing bends up to 150 degrees; if pressurized with 90kPa, it exerted less than 6N of normal force at the tip; a maximum force generates pressure of 44.17 mmHg at the tip (significantly lower than safe intraluminal human colonic pressure, i.e., 80 mmHg).

Research Robotic Colonoscopes (8)

- Pneumatic Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Manfredi et al. 2019 Soft pneumatic inchworm-like double balloon colonoscope (SPID)	Pneumatic actuation.	Two inflatable distal balloons for anchorage into the colonic wall, connected by a 3-DoFs central pneumatic actuator for a bio-inspired inchworm-like locomotion and bidirectional bending; external diameter of 18 mm, total length of 60 mm and weight of 10 g.	Soft and deformable structure aimed at reducing the pressure applied to the colonic wall and consequently pain and discomfort during the procedure; tested in a deformable in-vitro synthetic colonic phantom, mimicking shape and dimensions of the human anatomy; efficient navigation with an average forward speed of 2.8 mm/s (a total length of 1.4 m was covered in less than 9 min); manual withdrawal, pulling the tether with an average speed of 25 mm/s, in about 1 min.

Research Robotic Colonoscopes (9)

- Pneumatic Actuation.

Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Consis Medical Ltd. Semi-disposable and self-propelling robotic colonoscopes	Hydraulic actuation.	Semi-disposable and self-propelling robotic colonoscopes using hydraulic-aiding internal propulsion; composed of: (1) an inverted single-use inflatable sleeve, (2) a multiple-use electronic head, embedding a working channel, a camera, light source and air and water nozzle, and (3) an external control unit; once the electronic head is mounted and inserted into the anus, first the colon is inflated and then the device is deployed, aiding its navigation with an internal water-based hydraulic propulsion.	Hydraulic-aiding internal propulsion allows to gently approach colonic curves with a potentially-lower stress, and thus pain; examination performed withdrawing the device manually, pulling the tether and bending the camera with 2-DoFs.

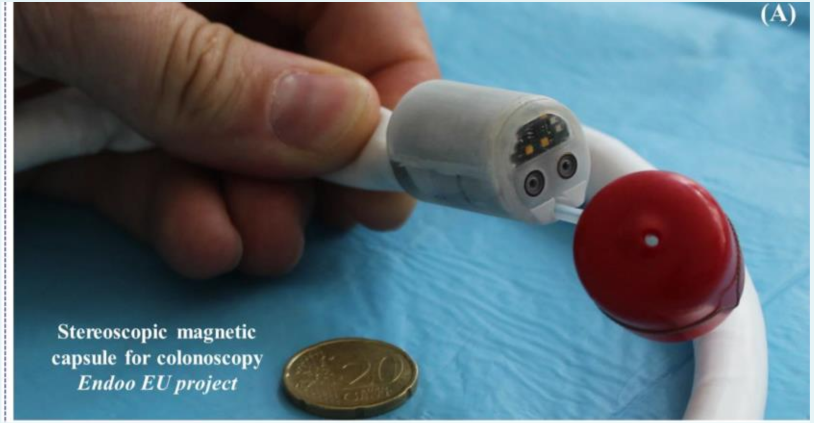
Research Robotic Colonoscopes (10)

- (Electro-) Magnetic Actuation.

Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Ciuti et al. 2010, Valdastri et al. 2012 VECTOR European project	Magnetic actuation (permanent magnets).	Magnetic-based accurate locomotion of wireless and soft-tethered capsules; use of permanent magnets embedded into the capsule and as the external source controlled by a robotic arm; continuous upgrade of the soft-tethered system in terms of modelling, localization and control towards autonomous locomotion.	Wired solution represents a trade-off between capsule and SC combining the benefits of low-invasive navigation (through "front-wheel" locomotion) with the multifunctional tether for conventional treatment; ex-vivo tests in explanted porcine colon (length of 850 mm) performed by 12 users with six to eight coloured beads, measuring 5 mm in diameter, randomly installed (number and position) along the internal surface of the colon; mean percentage of identified beads of 85 ± 11% (range 64–96%) and identified beads successfully removed; mean completion time, i.e., inspection and bead removal, of 678 ± 179 s (range 384–1082 s); preliminary in-vivo tests in pigs demonstrated an average distance travelled of 800 ± 40 mm in an average time of 900 ± 195 s, including the time devoted to inserting the tool into the dedicated channel and operating the instrument.

Research Robotic Colonoscopes (11)

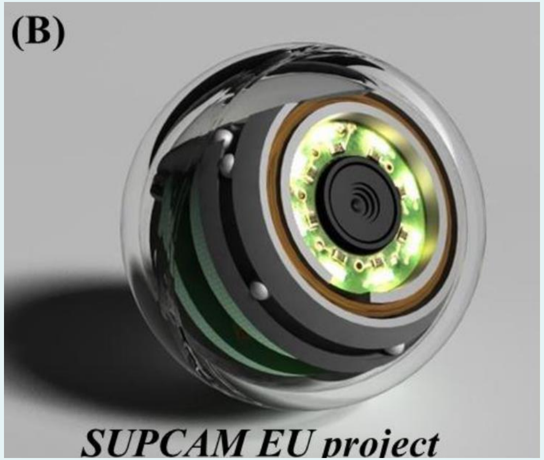
- (Electro-) Magnetic Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
ENDOO European project Soft-tethered stereoscopic robotic capsule colonoscope	Magnetic actuation (permanent magnets).	Soft-tethered magnetically-driven colonoscope with a Full-HD 170° FoV and 3–100mm DoF stereo-camera with a custom-made optics navigated by an external permanent magnet through a collaborative industrial anthropomorphic robot; advanced AI-based tools for augmented diagnosis.	Extensive experimental sessions in ex-vivo (preclinical outcomes under publication), and tests in human cadavers.

Research Robotic Colonoscopes (12)

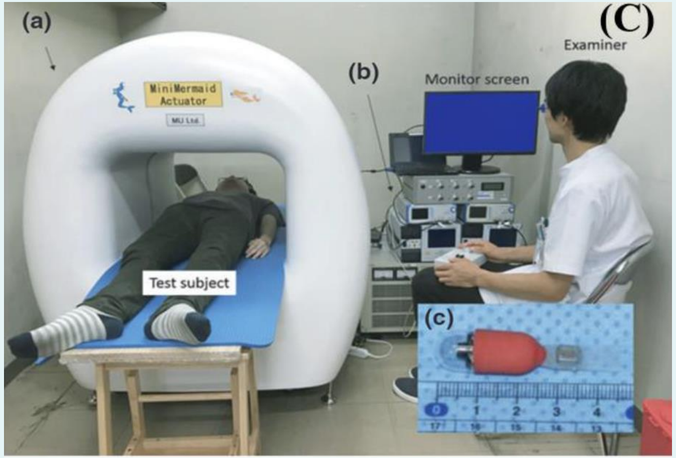
- (Electro-) Magnetic Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
SUPCAM European project Spherical-shape magnetic capsule for colonoscopy	Magnetic actuation (hybrid).	Spherical colonoscopic capsule embedding a permanent magnet and guided by an external gravity-compensated hand-guided electromagnetic system (static electromagnetic field); omni-directional view, by a single embedded camera, through 360° rotation of an internal magnetic frame into a transparent spherical shell.	Reliable navigation in ex-vivo (explanted porcine colon) and in-vitro (synthetic plastic phantom) conditions; in-vitro tests performed by five novice users, completing the task (i.e., locomotion in a ~900 mm long simple and rigid tube with curves) with a time of 44 ± 8 s (range 26–67 s).

Research Robotic Colonoscopes (13)

- (Electro-) Magnetic Actuation.



Device	Actuation Principle	Technical Distinctive Features	Clinical-Oriented Features, Studies, and/or Preclinical Outcomes
Nouda et al. 2018 PillCam™ SB2 capsule with an attached silicone magnetic fin	Magnetic actuation (hybrid).	Electromagnetic locomotion (alternating electromagnetic field through an external platform) of a 3D self-propelling capsule endoscope composed by a PillCam™ SB2 with an attached silicone fin, embedding a permanent magnet; modified capsule, 45mm in length and 11mm in diameter.	In-vivo human healthy volunteer test; the capsule, inserted in the anus and transported with endoscopic forceps in the descending colon, was able to swim in the lumen in antegrade and retrograde directions without any damage to the mucosa.

Thank you for your attention!

Any questions?